Validation of the new GEM Design for Discharge and Crosstalk Mitigation

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UoS Lectures

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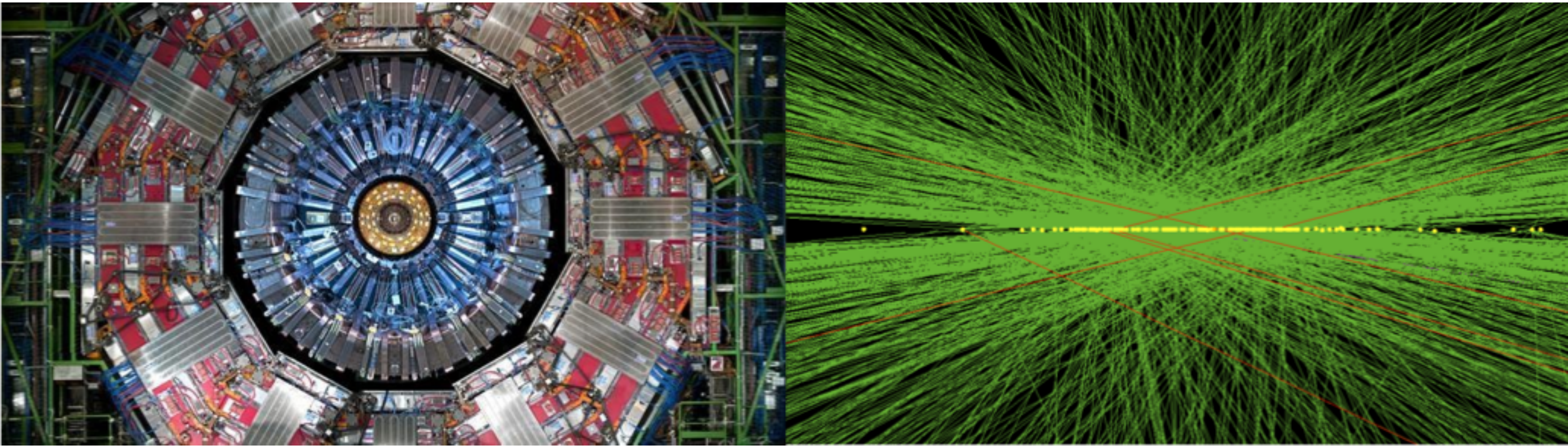


Summary

GE11 to GE21 – Design Change Motivation
- Discharge propagation principle
- Specificity of the discharge propagation in large detectors
- Propagation probability vs foils capacitance
- Double-segmented design and discharge protection

Towards the double-segmented design

Crosstalk Effect in Double Segmented Configuration
- Crosstalk - general description
- Crosstalk - signature
- Crosstalk Probability and Rate Estimation
- Electronics inoperative time
- Physics simulation

Highlight the problem of crosstalk with the double-segmented design

Crosstalk Mitigation Strategies
- Mitigation in other GEM groups
- Merging HV segments together
- GE21 Single segmented test confirmation
- Physics simulation comparison

Towards the mixed design configuration

Optimization – Final configuration Configuration
- Basic principle
- Discharge Protection
- Detector performance
- Crosstalk Probability and Rate Estimation
- Crosstalk characteristics comparison
- Physics simulation

Validation of the final GE21 configuration based on the mixed design

GEM foil Production
- Impact of the design change on foil production
- Impact on Schedule
- Production readiness at CERN
- Production readiness in Korea

Status of the production

From GE1/1 to GE2/1 foils
– Design Change Motivations –

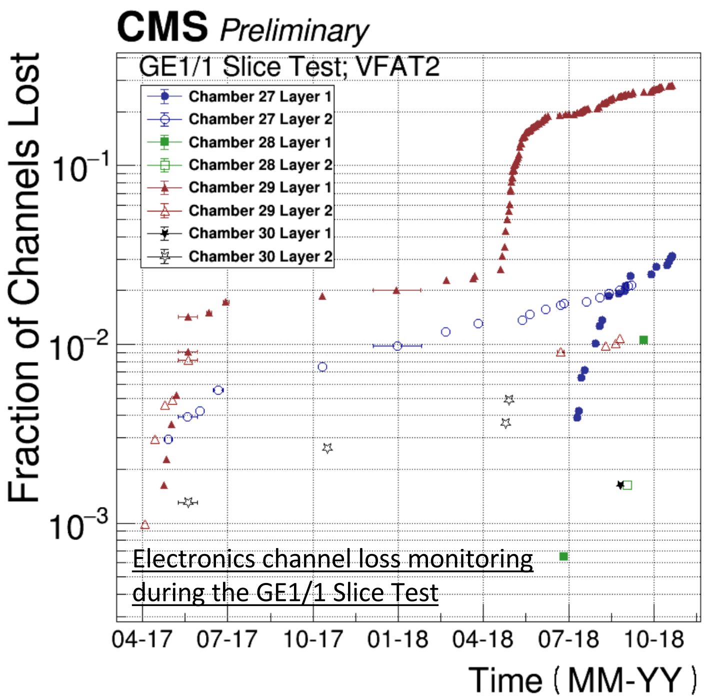
GE11 Slice Test Experience

GE1/1 Slice test:

- First operational experience in the real CMS environment
- First observation of discharge propagation
- Experienced VFAT3 channel loss

→

Start of a new discharge R&D campaign to cope with discharge propagation
(+ define new setups and protocols to reproduce the problem in the lab)



Channel loss :

- GEM discharges are normally confined within the GEM holes
- Discharges can propagate toward the readout board
- Possible damage of the electronics

Channel loss ∝ Discharge probability x Propagation probability x Damage probability

The most effective mitigation consists of reducing the probability of **discharge propagation**

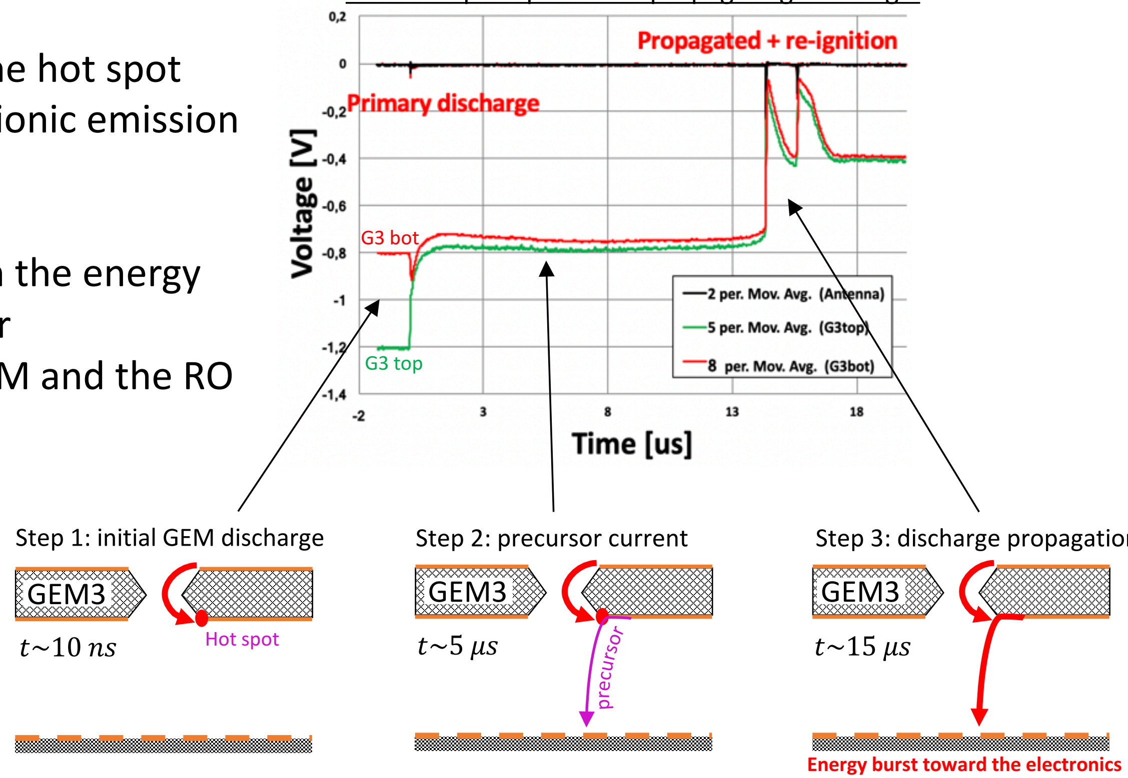
Discharge Propagation Principle

Step1: the **primary discharge** develops across the GEM layers (short circuit)

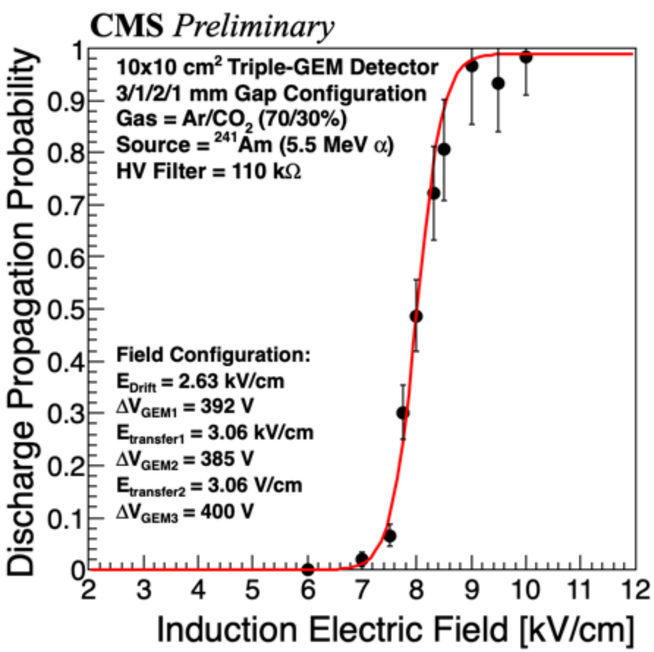
Step2: a **precursor current** arises from the hot spot created by the primary discharge (thermionic emission enhanced by the Schottky effect)

Step 3: the precursor current grows from the energy available in the foil to become a streamer
→ **secondary discharge** between the GEM and the RO

Oscilloscope capture of a propagating discharge

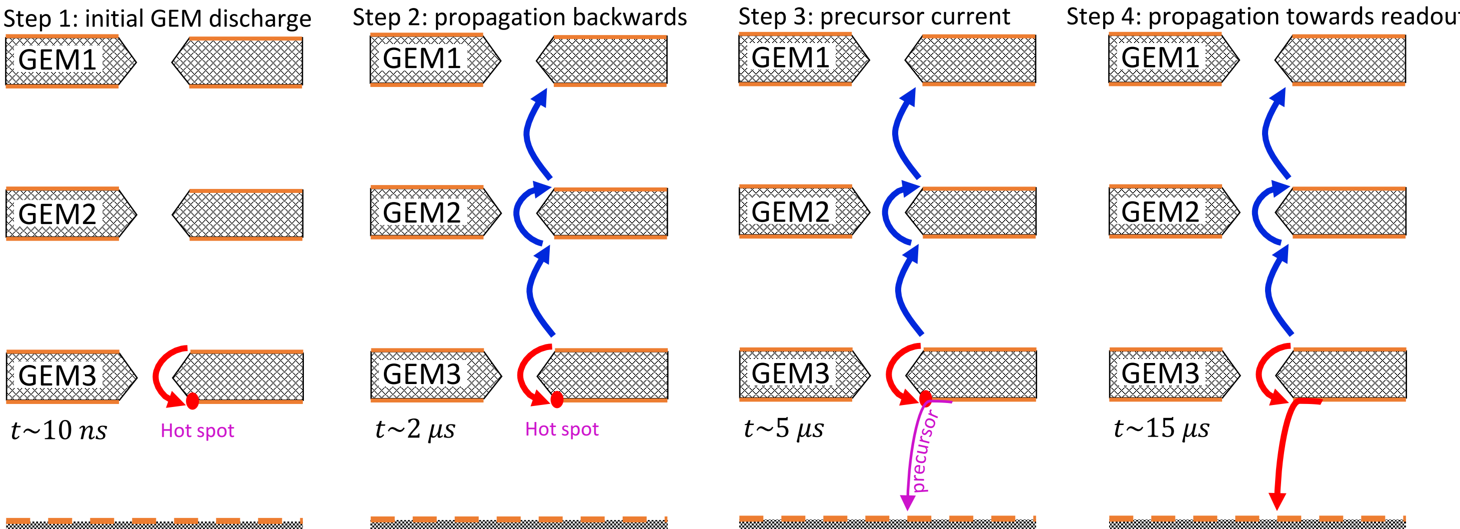


Schematic view of the discharge propagation process

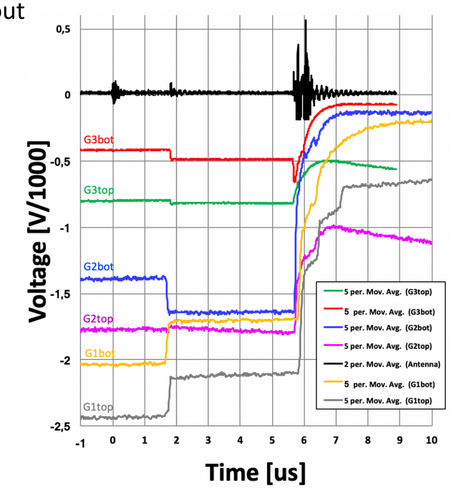


The probability to observe a discharge propagation in small detectors is **insignificant** below inductions fields of **7 kV/cm**:
→ CMS GEM typical induction field = **4.1 - 4.5 kV/cm**

Discharge Propagation in Large Detectors



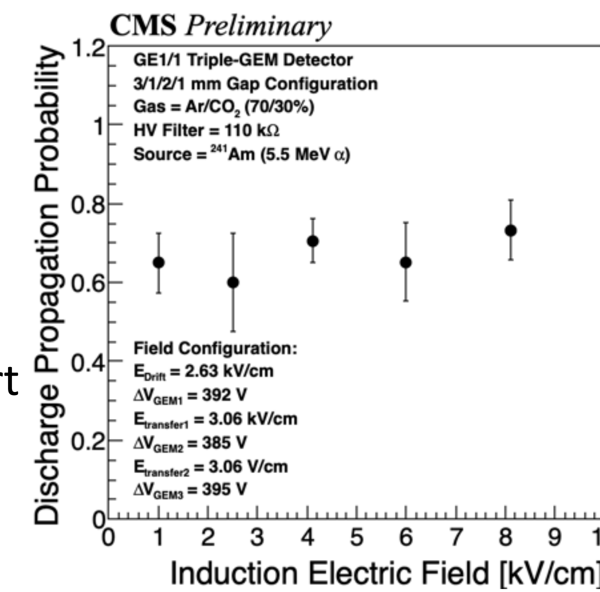
Schematic view of the discharge propagation process in large detectors



Oscilloscope capture of a propagating discharge

More complex propagation in large detectors:

- The primary discharge is systematically followed with a propagation backward **GEM2** and **GEM1**
- The backward propagation "gives" the primary discharge the strength to propagate **toward the readout** even at **low induction fields**
- After a full propagation, the electronics is connected (via short circuits in the gas) to all the GEM electrodes

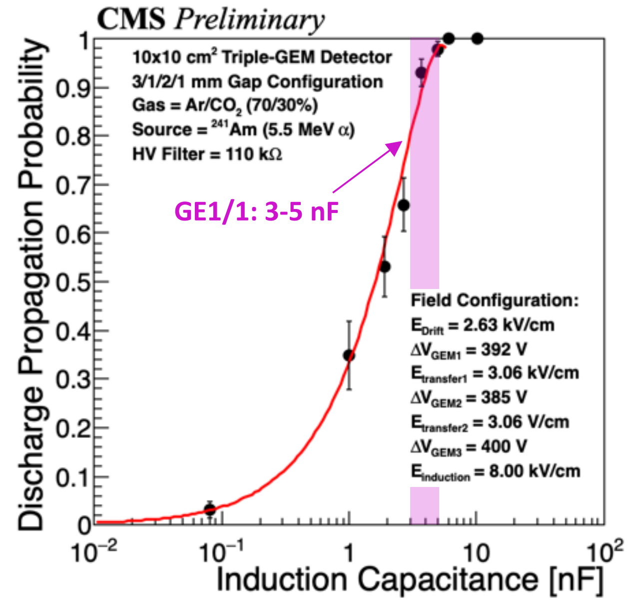


The probability to observe a discharge propagation in large detectors is **significant** even at **low inductions fields**

Propagation Probability vs. Capacitance

Large reservoir of energy:

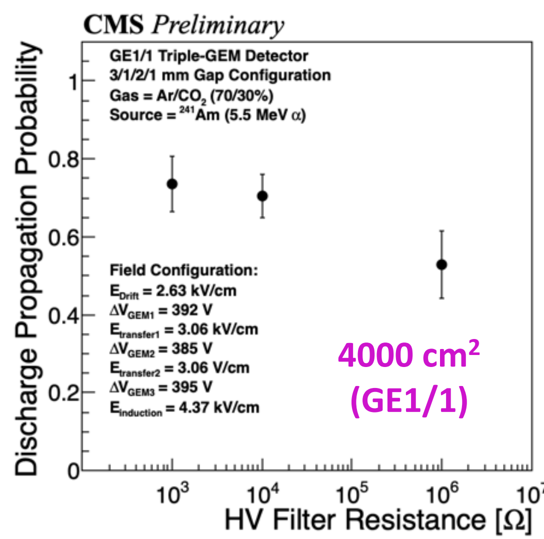
- The probability to for a discharge to propagate depends on the **gap capacitance**
- A large gap capacitance means more energy to **feed the precursor current** and trigger the streamer development
- GE1/1 foils typically have enough **energy stored** in the gap to trigger the propagation, even at low induction field

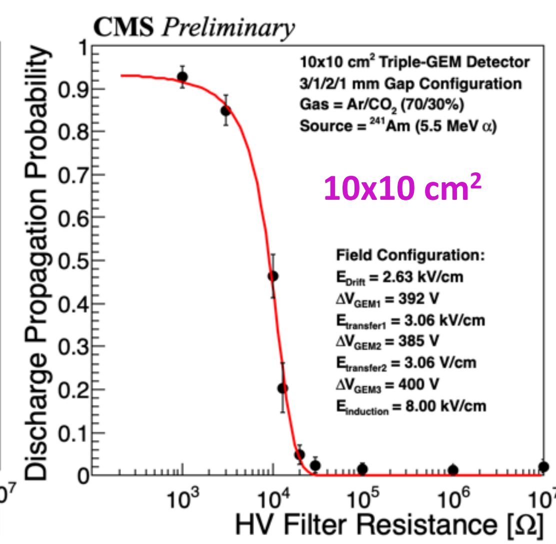


Influence from outside:

- The energy stored "outside" the GEM foil can participate to the discharge propagation
- The **filter resistance** helps to prevent energy transfer to the foil

GE1/1-size foils contain enough energy to maintain an almost-systematic discharge propagation without the help of external energy
→ Reducing the gap capacitance would give back the control on the energy

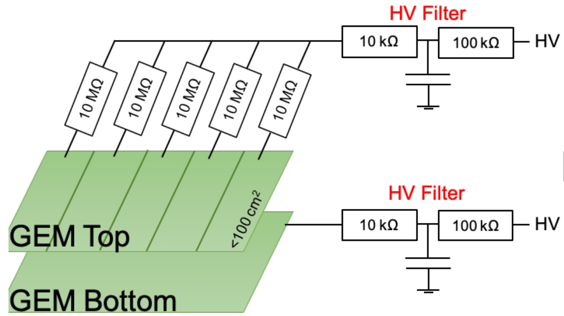




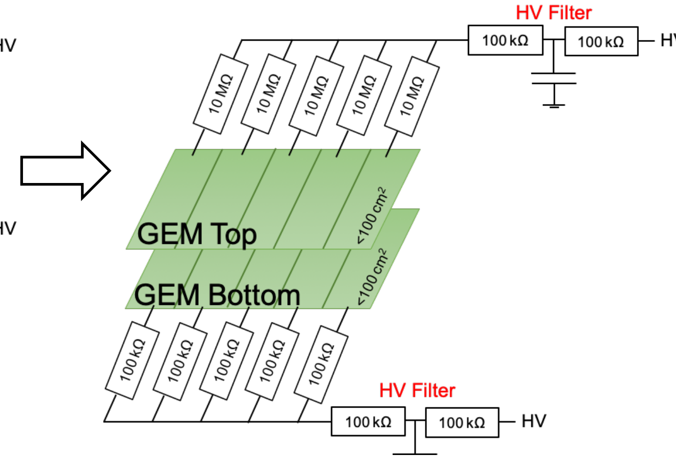
Double-Segmented Design

<u>Basic principle:</u>

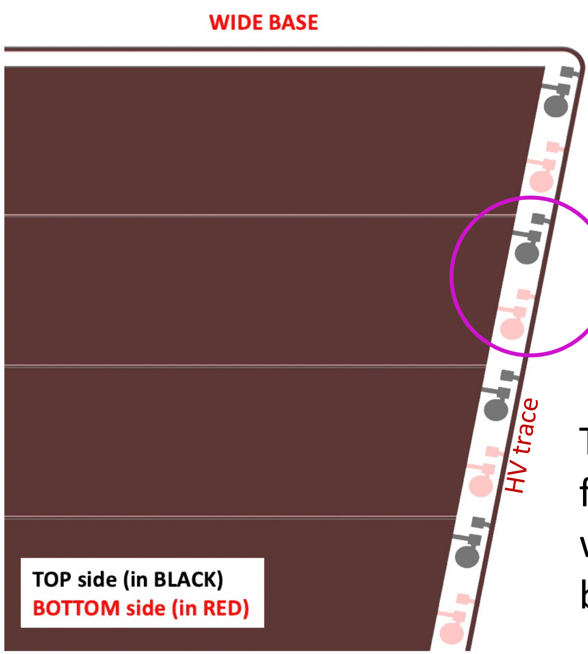
- **Top segmentation** : GEM protection against regular discharges
- **Bottom segmentation**: protection against discharge propagation



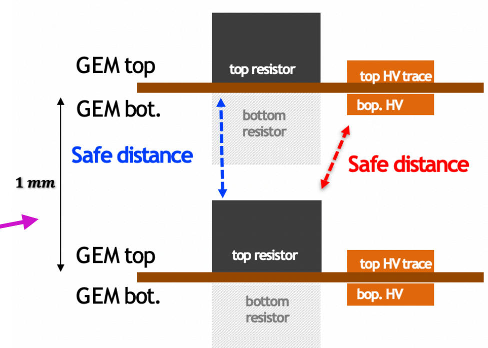
"Single-segmented" GEM foil concept



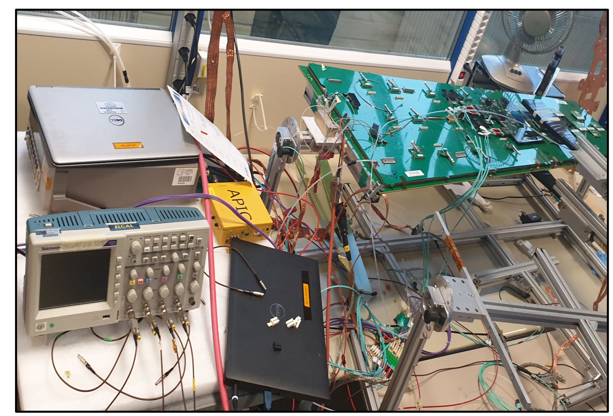
"Double-segmented" GEM foil concept



"Double-segmented" GEM foil Layout



Top and bottom resistor footprints are shifted to avoid weak points (possible electrical breakdown of the gas)



Full GE1/1 prototype with three double-segmented GEM foils: passed all QC and stability tests

Double-Segmented Design

Small detector (reference):

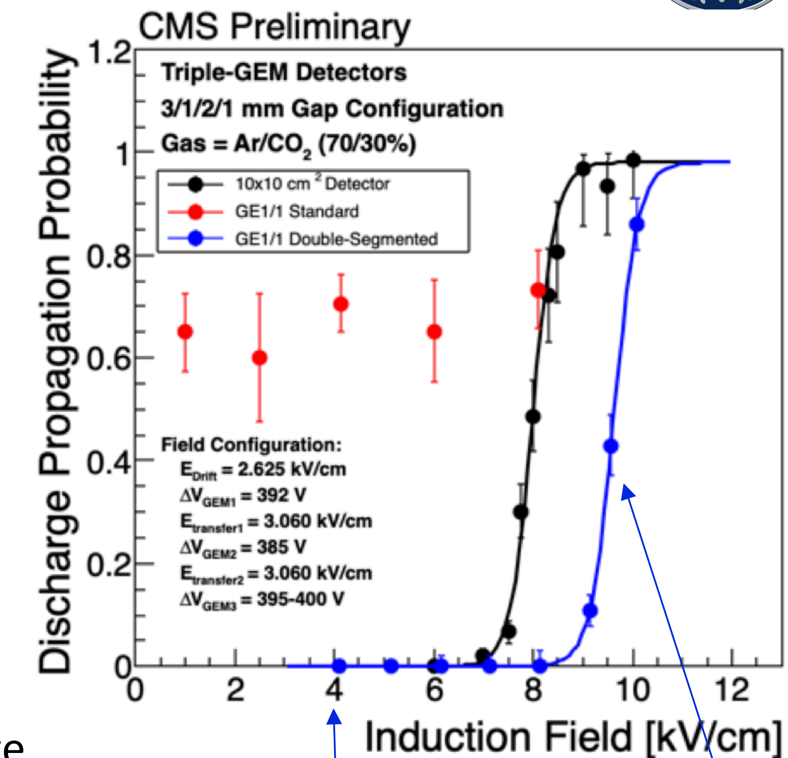
- The propagation probability arises above 7 kV/cm; it involves only GEM3 and the RO board

GE1/1 single-segmented:

- The propagation probability is constant around 0.7; it involves all GEMs and the RO board

GE1/1 double-segmented:

- propagation probability arises above 8 kV/cm; it involves only GEM3 and the RO board

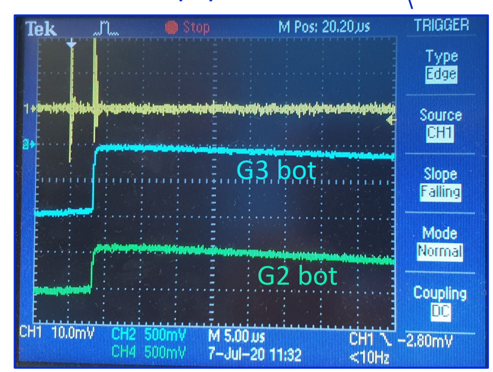


Upper limit at 4.12 kV/cm: $Pd_{propa} < 3\times10^{-4}$

The discharge behavior in the double-segmented large detector is similar to the one in the small reference chamber:

→ Better **control** of the energy

→ Significant **reduction** of the propagation probability



With the double-segmented design, the discharge propagation probability is reduced by a **factor > 10^4**

Crosstalk Effect in the Double-Segmented Configuration

Plot to be updated

Crosstalk – General Description

<u>Side effect of using double-segmented design on GEM3:</u>

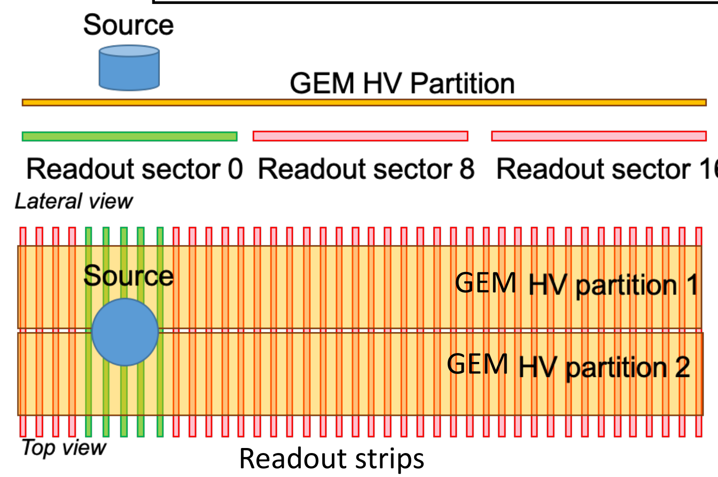
- Reducing the size of the HV segments on the last GEM increases the HF impedance to ground:

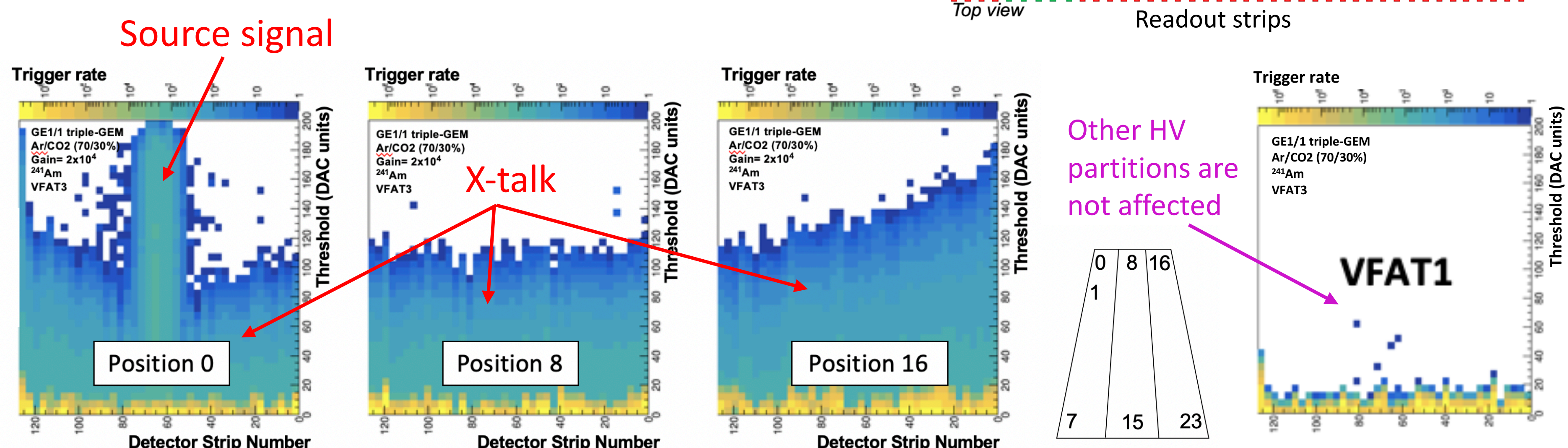
→ Induces **cross-talk**

→ All strips facing the **same HV partition** can suffer crosstalk

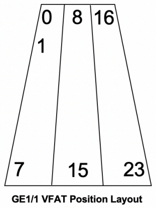
→ In case of **large signals (HIP)**, the corresponding crosstalk signals can trigger the electronics and make the channels unusable for several BX

Start of a R&D campaign to cope with the crosstalk issue



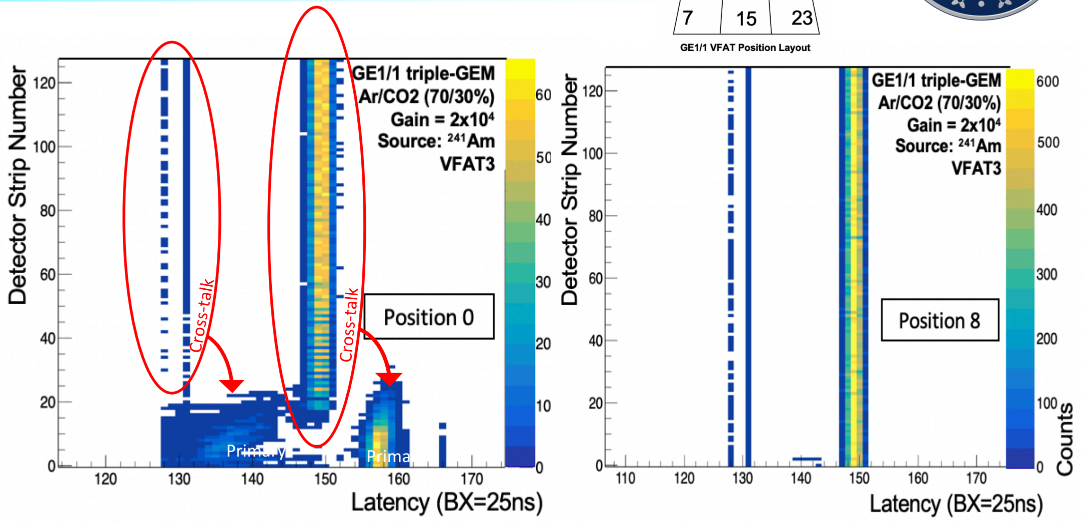


Crosstalk - Signature



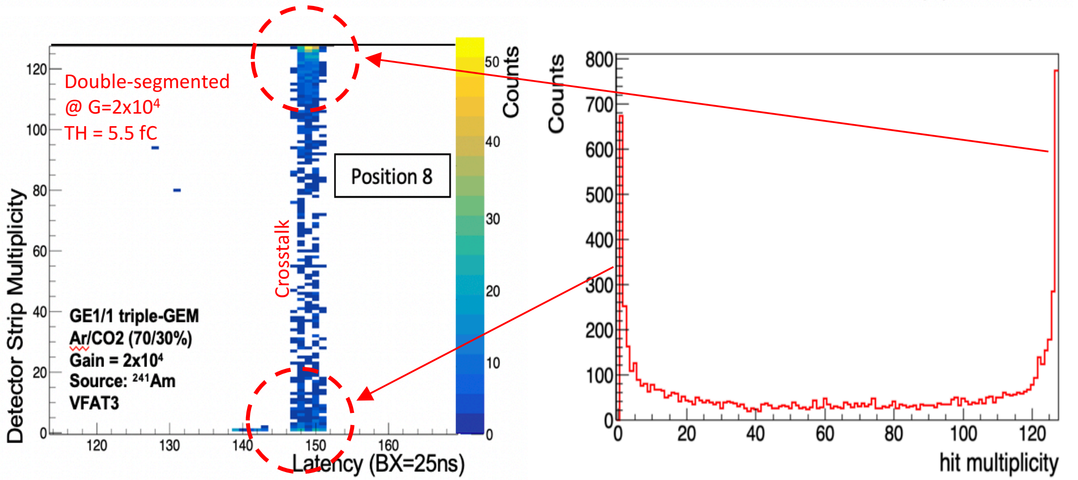
Timing characteristics:

- Each primary signal structure has its own cross-talk structure coming after **10 BX** (250 ns)
- Probability of cross-talk depends on the amplitude of the primary signal (expected)



Range and probability:

- Eventually, all channels sharing the same HV partition are affected by the cross-talk
- On average, **61%** of the channels are seeing the same crosstalk signal for a given event

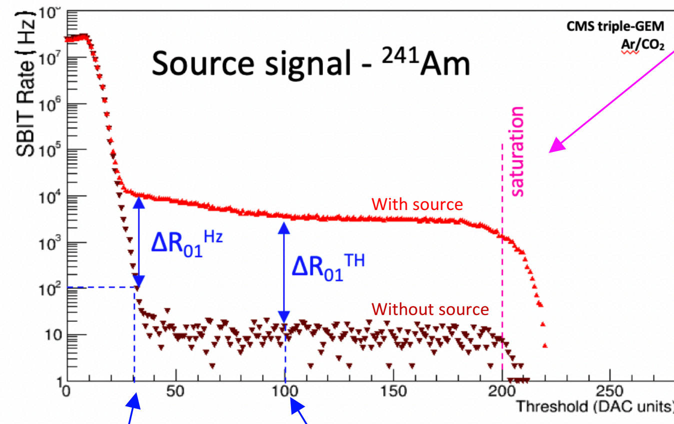


Crosstalk signals are typically affecting **61% of the channels** sharing the **same HV segment**, with a **delay of 250 ns** with respect to the original signal

Crosstalk - Probability

Probability measurement:

- At fixed threshold to estimate the rate for the highest amplitude signals
- At nominal threshold (= 100Hz of noise)



Saturation:

→ Not possible to **quantify the max amplitude** of a signal if the SBIT rate drops around 200 DAC units

→ A "plateau like" rate profile indicates that the signal is above the VFAT range

ARMDAC 100 = 14.1 ± 2.1 fC
(may vary a bit from one VFAT to another)

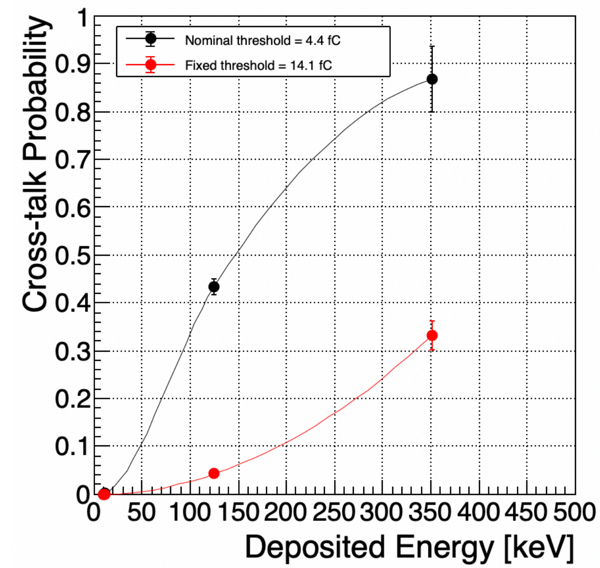
ARMDAC 30 = 4.4 ± 0.6 fC
(may vary a bit from one VFAT to another)

Crosstalk probability:

$P_{XT}^{TH} = \Delta R_{neighbourg}^{TH} / \Delta R_{source}^{TH}$ → at fixed threshold 100 DAC units

$P_{XT}^{Hz} = \Delta R_{neighbourg}^{Hz} / \Delta R_{source}^{Hz}$ → at nominal threshold 100 Hz noise

Crosstalk probability in double-segmented foils becomes problematic for energy deposits above **30 keV**. X-rays and lower ionization particles **do not trigger** crosstalk

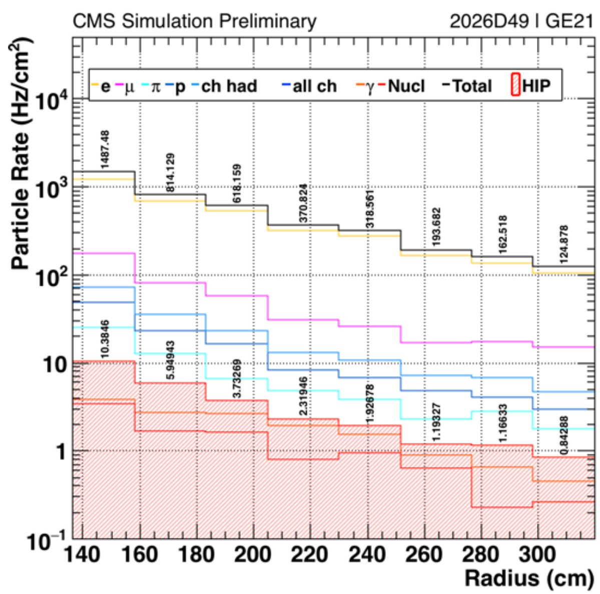


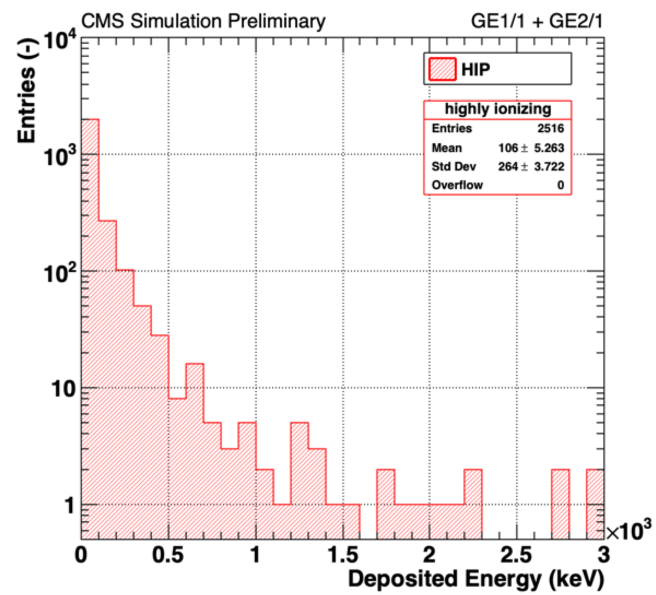
Crosstalk – Rate Estimations

Evaluation of the Crosstalk rate in CMS:

- Prediction of the total particle rate per eta partition of a single GE2/1 chamber
- Simulation including neutron background hits has been performed with GEANT
  - Total hit rate of Highly Ionizing Particles (HIPs) (mostly protons and nuclei) depositing 30 keV or more
- The HIP rate can be convoluted with the energy-deposit dependent probability to create a cross talk signal to obtain the prediction of the cross talk signal rate

BKG population susceptible to **trigger crosstalk** is derived from the 30 keV energy cut: up to **10.4 Hz/cm²** in the hottest GE21 region. The average energy deposit for this population is **107 keV**



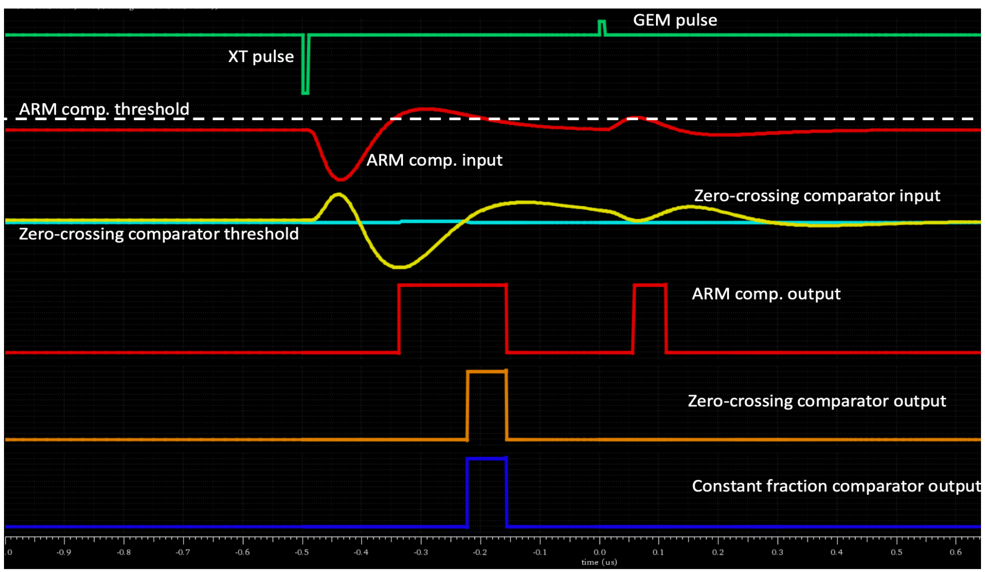


GEANT4 based simulation model including the latest CMS configuration (with all subdetectors upgrades)
CMSSW 11_0_0_pre13 Min Bias collisions with hit time 100ms

Electronics Inoperative Time

Cross-talk effect on electronics:

- Bandwidth occupancy: not a major problem since cross-talk signals have a very clear signature and can be **filtered-out** at the front end level
- But channels activated by cross-talk are not ready for other “good” events during an **inoperative time** period
- The inoperative time is evaluated by simulating the **injection of parasitic signals** (with the crosstalk characteristics) on top of muon signals:
  - Varying the charge of the parasitic signals from 5 fC to 1200 fC
  - Varying the injection time with respect to the muon signal from –1 μs to +0.2 μs by steps of 5 ns

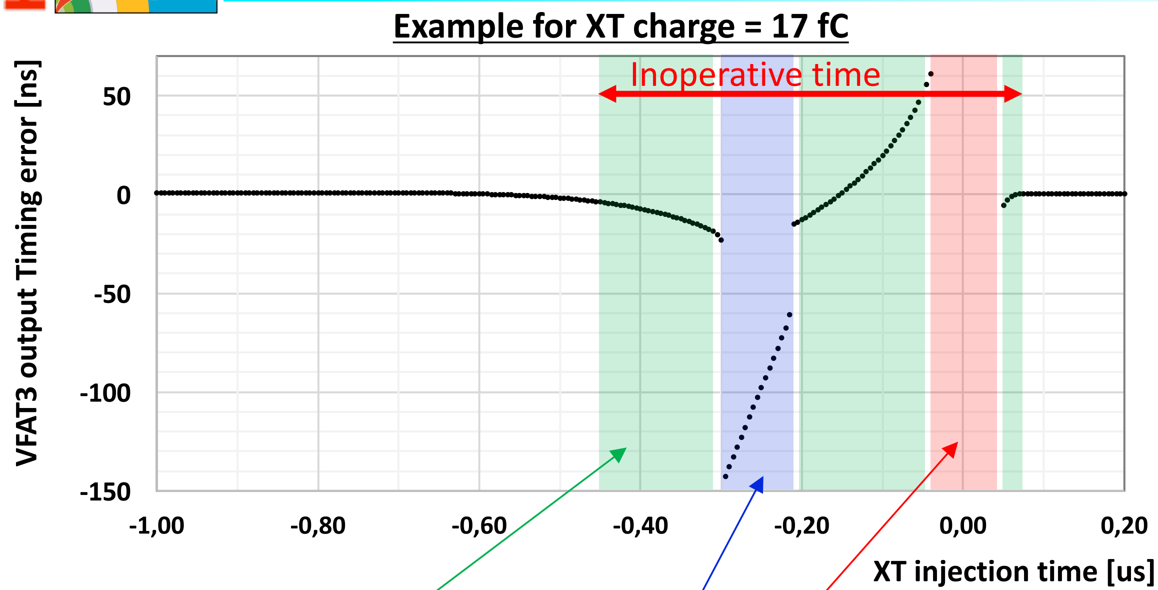


Example of the VFAT response to a crosstalk event (simulation)

→ NB: the in operative time strongly depends on the ratio between the crosstalk and GEM charges; and on the VFAT settings, in particular the shaping parameters and the comparator threshold

→ Simulation based on the standard sets of parameters

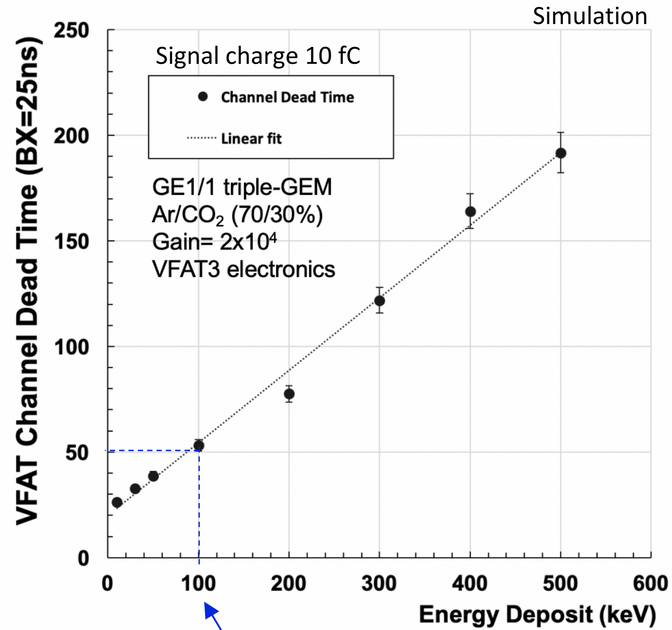
Electronics Inoperative Time



GEM signal timing is off: the voltage baseline at the input of the comparator is biased by the tail of the crosstalk

GEM signal compensated by the crosstalk: no significant voltage at the comparator input

GEM signal dominated by the crosstalk: comparator already triggered

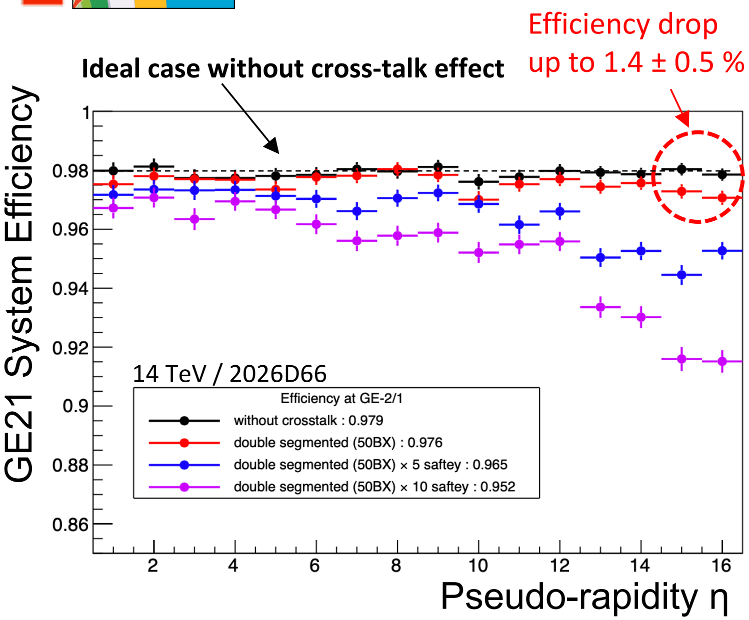


Average energy deposit in GE21

→ NB: the real crosstalk charge cannot be measured directly in the double-segmented configuration due to the saturation of the VFAT

Assuming the crosstalk amplitude is comparable to the HIP amplitude, the crosstalk signals leave the RO channels inoperative for **50 BX** in the double-segmented configuration

Physics Simulation



Simulation parameters:

- Event samples for Z → Mumu @ 14 TeV
- The **HIP rate** is estimated from the BKG simulation, convoluted with the crosstalk probability vs. **deposited energy** (> 30 keV)
- Each strip can possibly see the crosstalk of **two eta** partitions (because of the SBIT mapping)
- **Inoperative time** of **50 BX** based on the electronics simulation + *estimation* of the crosstalk charge

First order approximation given by:

Probability of inactive RO per event : $P_{DT} = \frac{HIP_{rate}}{BX} \times Prob_{XT} \times InoperativeTime$

Rate Normalized to 1 BX

Then the real chamber efficiency is : $Eff_{real} = Eff_{ideal} \times (1 - P_{DT})$

The **maximum** **efficiency drop** due to the crosstalk effect is **1.4 %** at the highest eta (conservative estimations but without safety factor)

→ **Necessary to find an alternative option**

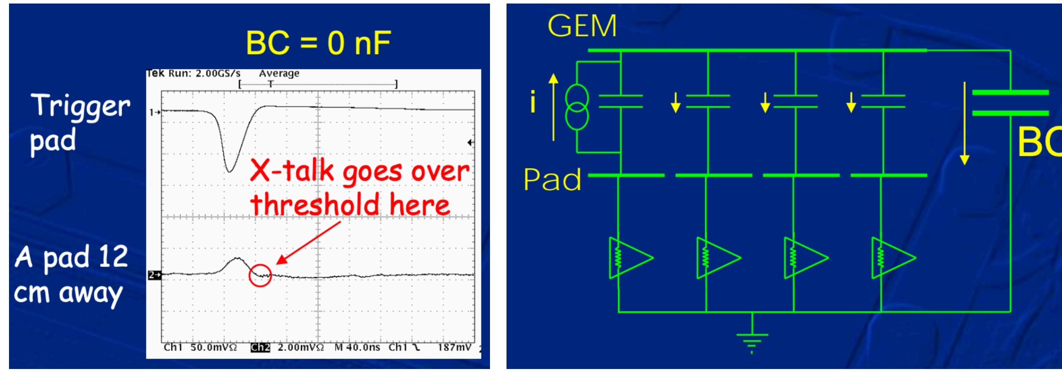
Crosstalk Mitigation Strategies

Crosstalk Mitigation in Other Experiments

LHCb Experience:

- Triple-GEM ~ 480 cm^2
- 3/1/2/1 configuration
- HV segments top ~ 80 cm^2
- HV segments bottom ~ none
- Induction Capa ~ 0.2 nF

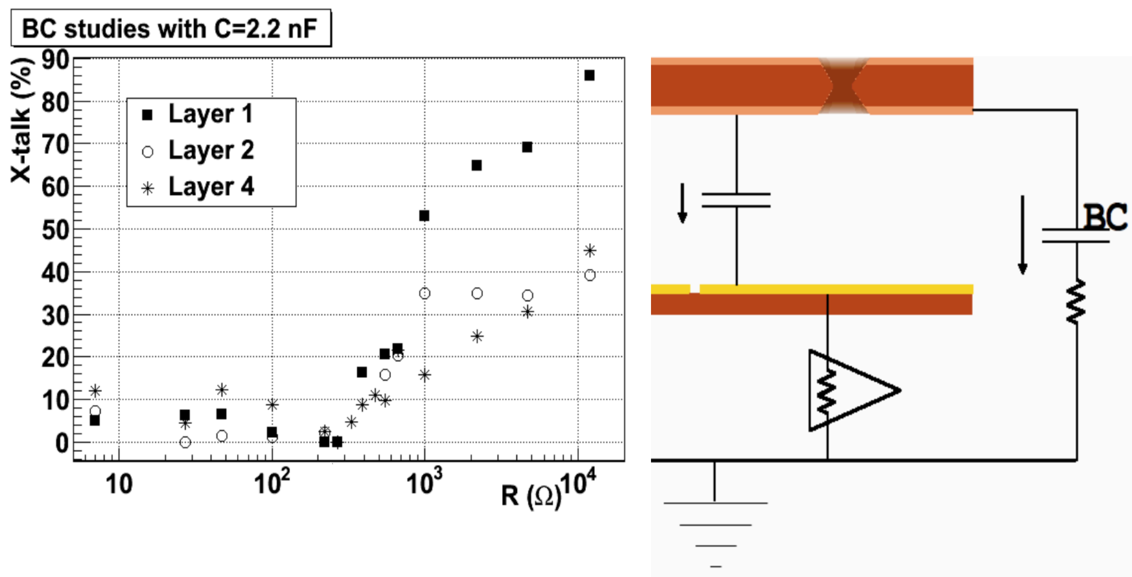
A. Cardini for the LHCb Collaboration (2006)
https://indico.cern.ch/event/473/contributions/1983755/attachments/954021/1353774/Cardini.pdf



KLOE-2 Experience:

- Triple-GEM ~ 2450 cm^2 (cylindrical)
- 3/2/2/2 configuration
- HV segments top~ 105 cm^2
- HV segments bottom ~ 615 cm^2
- Induction Capa ~ 0.8 nF

G. Morello for the KLOE-2 IT group(2013)
https://https://indico.cern.ch/event/258852/contributions/1589820/attachments/456014/632021/MPGD2013_morello.pdf



Crosstalk mitigation:

- Use of a **blocking capacitor** between G3 bottom and GND to bypass the induction gap:
  - LHCb: C_b = 0.7 nF
  - KLOE-2: C_b = 2.2 nF

Crosstalk Mitigation in Other Experiments

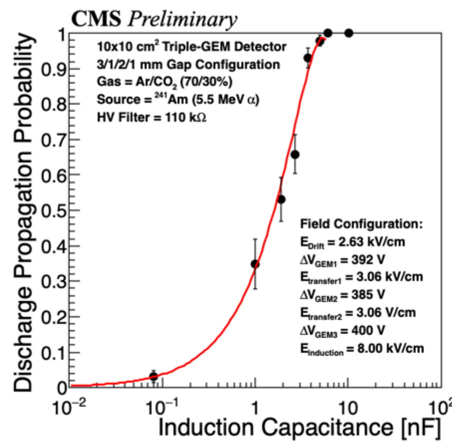
Technical limitations:

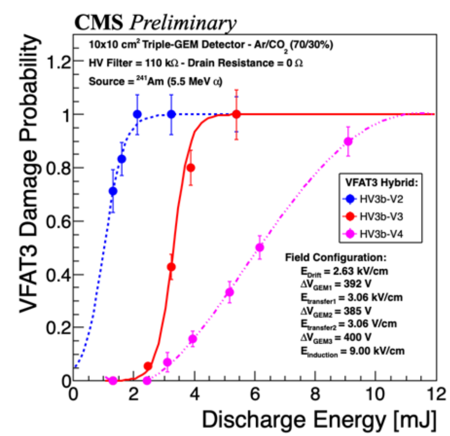
- GE2/1: 40 to 80 HV segments per foil → the blocking circuit must be inside the gas volume
- Significant re-design of the foils (add space for the RC components, bring GND line on the foil)
- Significant re-design of other detector components (DRIFT board, Mechanics etc …), possible reduction of the active area
- Introduce new weaknesses (e.g. long term failure of the capacitor)
- **Hard to find nF capacitors which can fit in a 1mm gap (including safe distance with other electrodes)**

Conceptual limitations:

- Adding the blocking capacitor means increasing the gap capacitance by a factor 3:
  - → **Increase of the discharge propagation probability (defeats the primary purpose of the double-segmented design)**
  - → **Increase of the discharge energy, i.e. the probability to damage the electronics in case of propagation**

	Induction C_i (nF)	Blocking C_b (nF)
LHCb	~ 0.2 nF	0.7
KLOE-2	~ 0.8 nF	2.2
GE2/1	**~ 2 - 3 nF**	**> 6 – 9 nF**

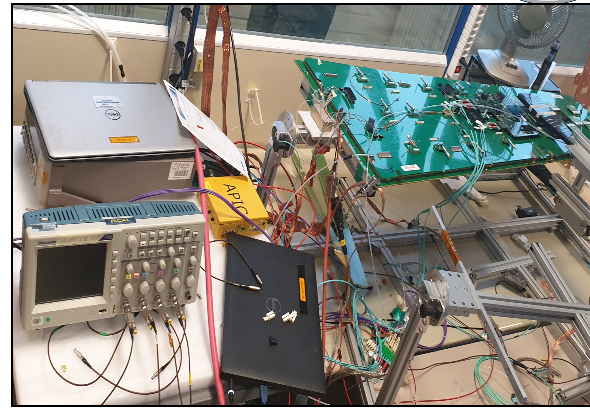




Investigating the HV sector size

Detector setup:

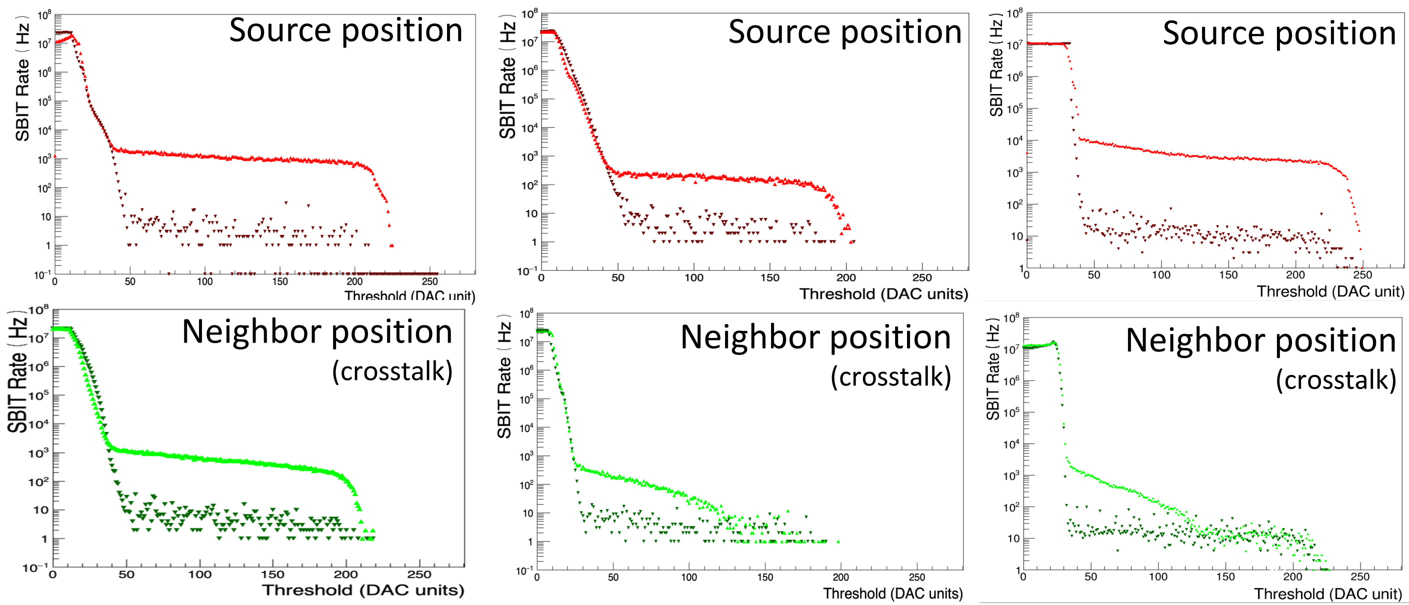
- GE1/1 prototype with double-segmented foils
- GEM3 bottom sectors are merged together by groups of 10 to represents larger HV segments
- 3 configurations are compared:
  - GE11 double segmented; segment size ~ **100 cm²**
  - GE11 with merged segments; segment size ~ **1000 cm²**
  - GE21 single segmented; "segment" size ~ **2500 cm²**



GE1/1 prototype with three double-segmented GEM foils

Clear **reduction** of the crosstalk **rate** and **amplitude** when increasing the size of the HV segments on G3 bottom
→ Best results obtained with the single segmented foil

100 cm² | **1000 cm²** | **2500 cm²**



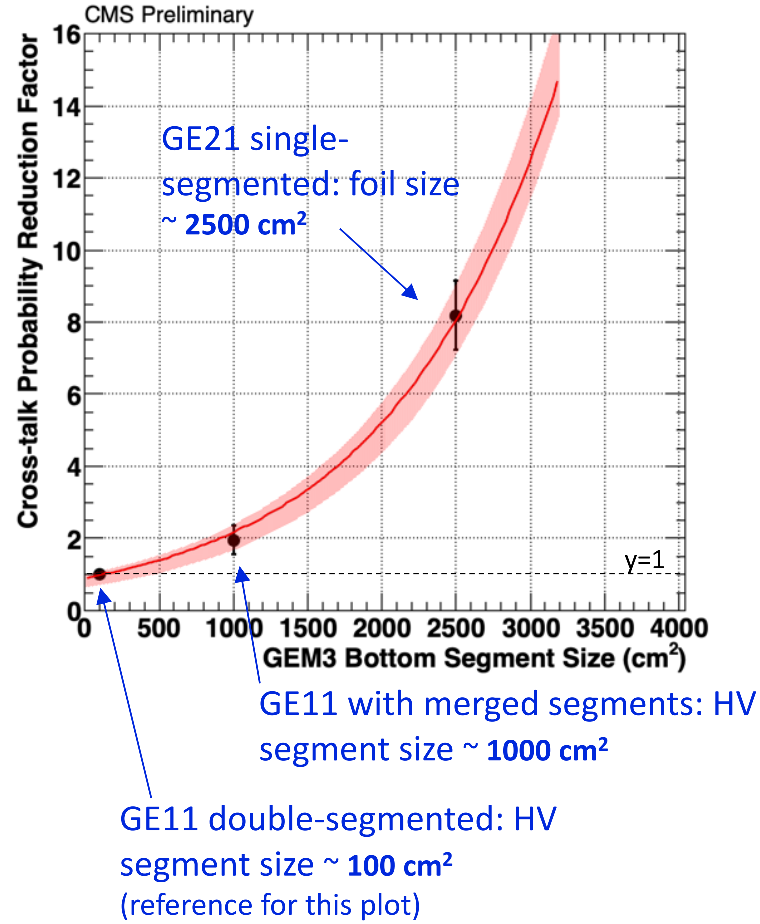
Investigating the HV sector size

3 configurations are compared:

- GE11 double segmented; segment size ~ **100 cm²**
- GE11 with merged segments; segment size ~ **1000 cm²**
- GE21 single segmented; “segment” size ~ **2500 cm²**

Improvements:

- Increasing the HV segments size helps to evacuate the crosstalk current and “dilute” the crosstalk effect over a larger surface
- Maximum segment size: ~ 1200 cm² (i.e. 2 segments per foil)
  - → Crosstalk probability reduced by a factor ~ 2.5
  - → Crosstalk amplitude reduced to less than ~ 20-25 fC



But the improvement is much less compared to a regular single segmented foil:

- Unnecessary **complication** of the design
- Both options would give **poor discharge mitigation**

The improvement of the crosstalk is **not sufficient** to justify the increasing of the HV segment size
→ better results are obtained by completely removing the bottom segmentation
→ **The real choice is between single-segmented or double-segmented with fine segments**

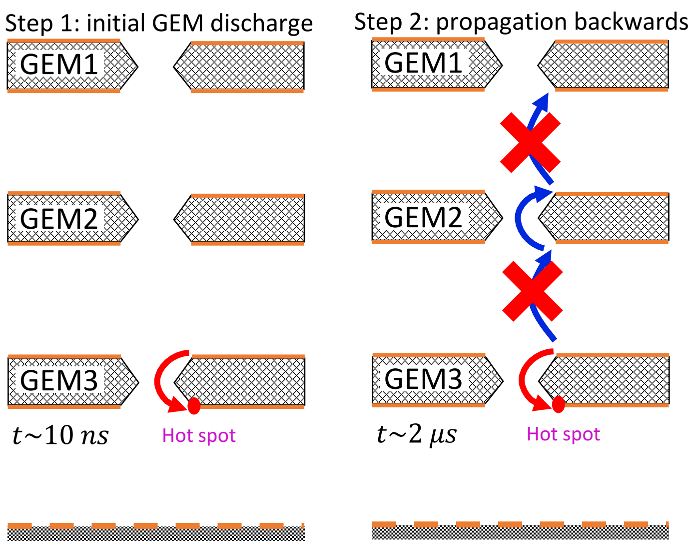
Final GE21 Configuration
- Based on the Mixed-Design -

Basic Concept

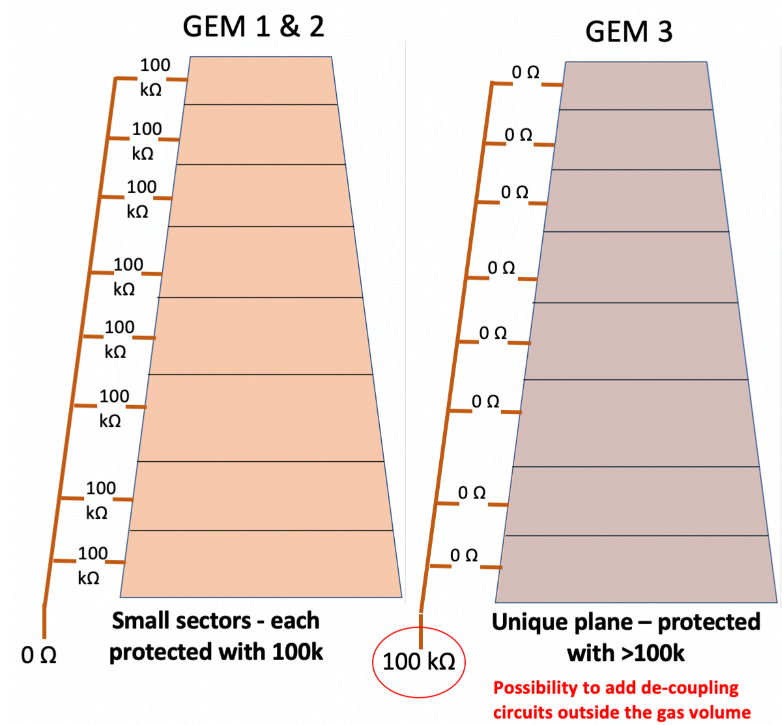
→ **Introducing the final configuration based on the "mixed" design:**

- GEM1 and GEM2 are **double-segmented** to prevent the **discharge propagation**
- GEM3 is **single-segmented** to suppress the **crosstalk**

  → The foil is actually double-segmented but the bottom segments are merged together using **0 Ω jumpers**



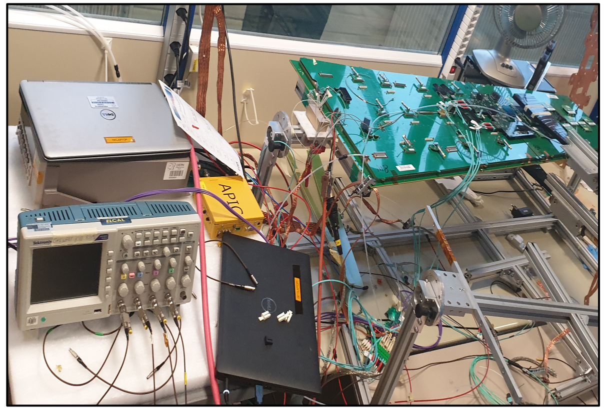
The propagation at low induction field can be stopped in the **transfer gaps** thanks to the double segmentation on the first GEMs
→ Propagation stopped before it can reach the RO



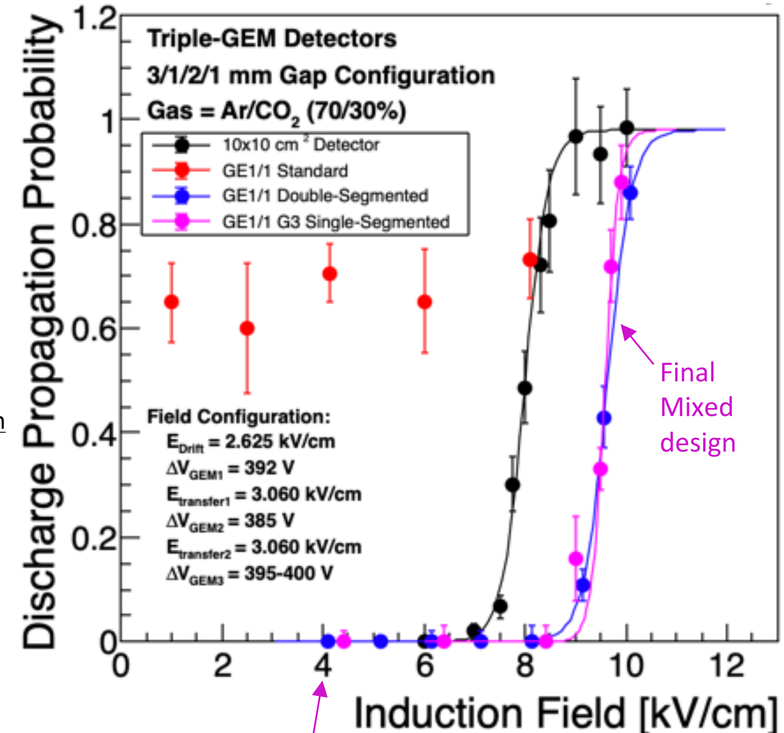
Merging the HV segments on the bottom of GEM3 allows to reproduce the single-segmented behavior while having the **same layout** for all the GEMs

Final Design - Discharge Protection

GE11 prototype with mixed design configuration:
- Size equivalent to the **largest GE21 modules**
- Large foils = larger gap capacitance = worst case scenario from the discharge perspective



GE1/1 prototype in the final mixed design configuration



Upper limit at 4.12 kV/cm: $Pd_{propa} < 3x10^{-4}$

Propagation mitigation:
- The propagation probability follows the **same behavior** as in the fully double-segmented configuration **= very effective mitigation**
- At nominal field (4.12 kV/cm) the probability is **$< 10^{-4}$**
- At extreme fields (> 8kV/cm) the propagation can take place but it is **much simpler** than in single segmented foils (i.e. straight propagation from G3 bottom to the RO board)

The final mixed design configuration gives the **same level of protection** as the fully double-segmented configuration

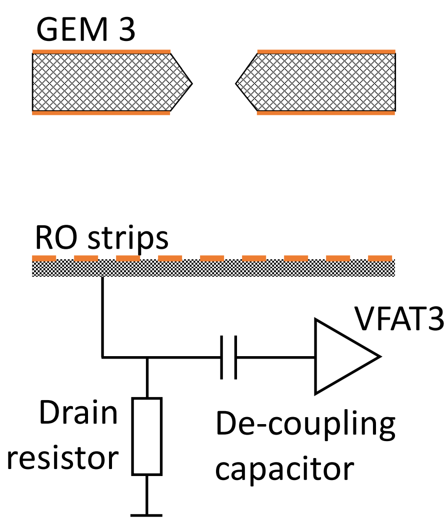
→ Improvement factor > 10^4 with respect to the GE1/1 baseline

(GE21 Plugin Card)

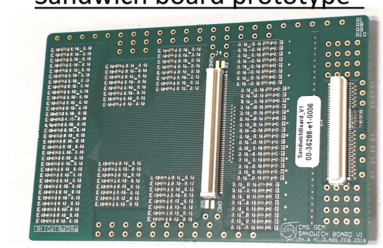
An additional layer of discharge protection on the readout side:

→ The discharge propagation can be stopped at the input of the RO strips using a drain resistor:

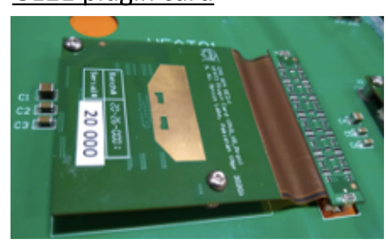
- the **precursor current** induced before the discharge propagation runs through the drain resistor
- the **voltage drop** across the drain resistor temporarily suppresses the **induction field**
- the precursor current is quenched and the discharge propagation **cannot happen**

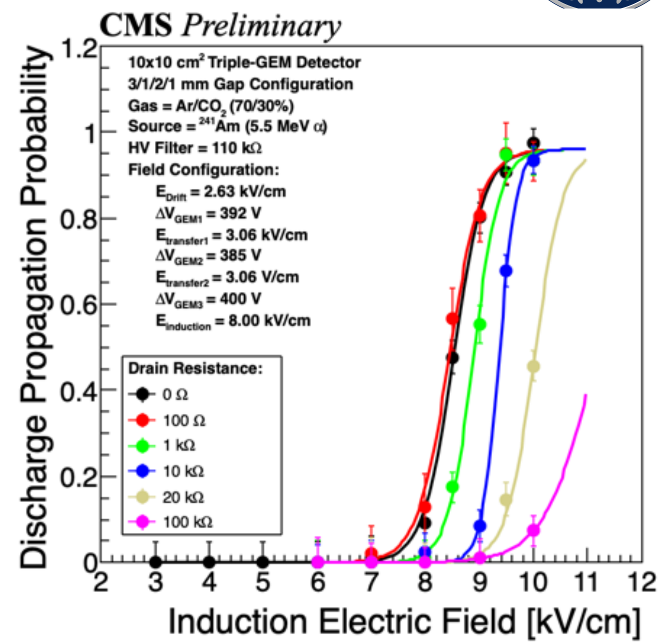


Sandwich board prototype



GE21 plugin card

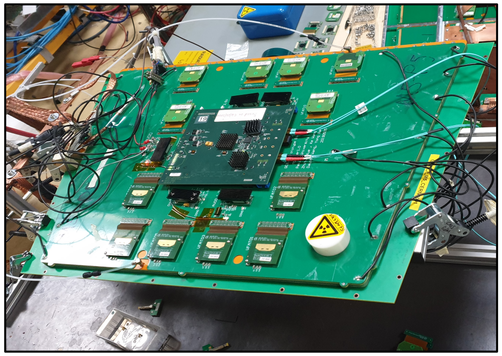




→ Tested on various prototype boards and implemented on the latest GE21 plugin cards for final verification

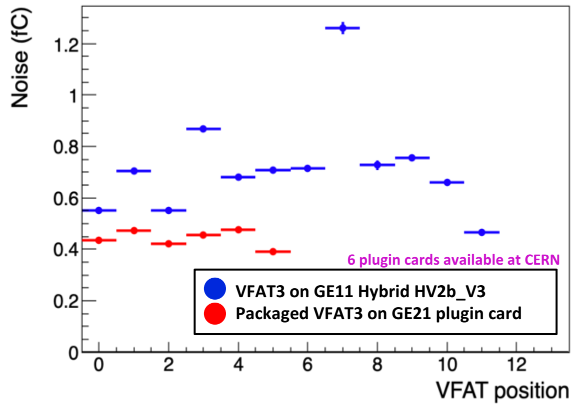
Possibility to add another layer of **discharge protection** in front of the VFAT:
→ with drain resistors as low as 100 kΩ, the propagation probability is reduced by a **factor > 10^3**

Final Design - Performances

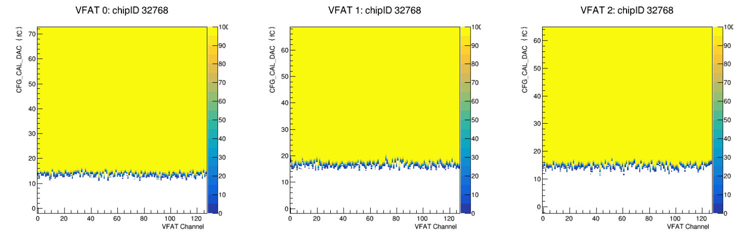


Production-like M5 detector with the final mixed design configuration

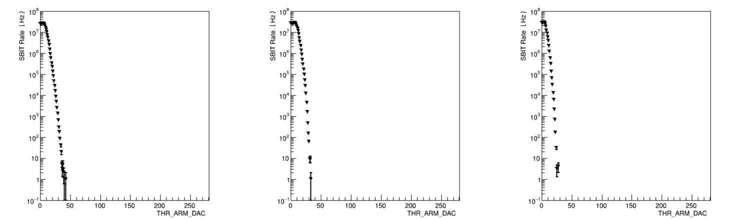
GE21 final design + plugin card: noise profile



GE21 final design + plugin card: S-curve

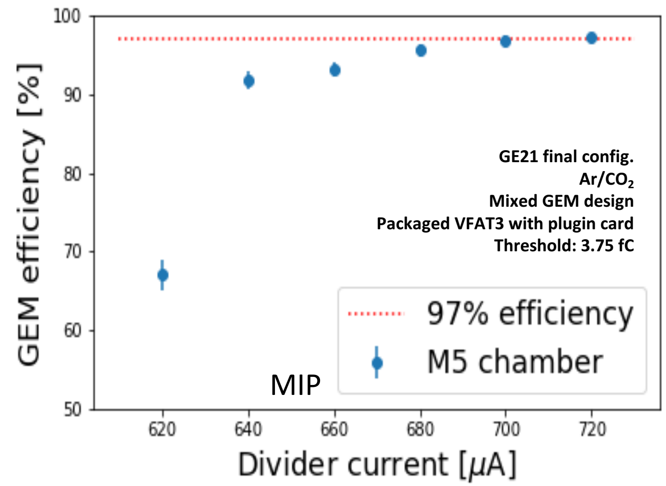


GE21 final design + plugin card: SBIT scans



Detector + electronics integration:

- Full system with mixed design configuration, final plugin cards and final electronics (**production-like prototype**)
- The chamber **passed all the QCs**, stability tests and electronics characterization tests
- All VFATs show a **uniform noise behavior** within the expectations with ENC ~ 0.5 fC (better than with the GE1/1 hybrids)
- The chamber reaches a MIP efficiency of **97.16 %** in the expected gain range (1 – 2 x 10^4)

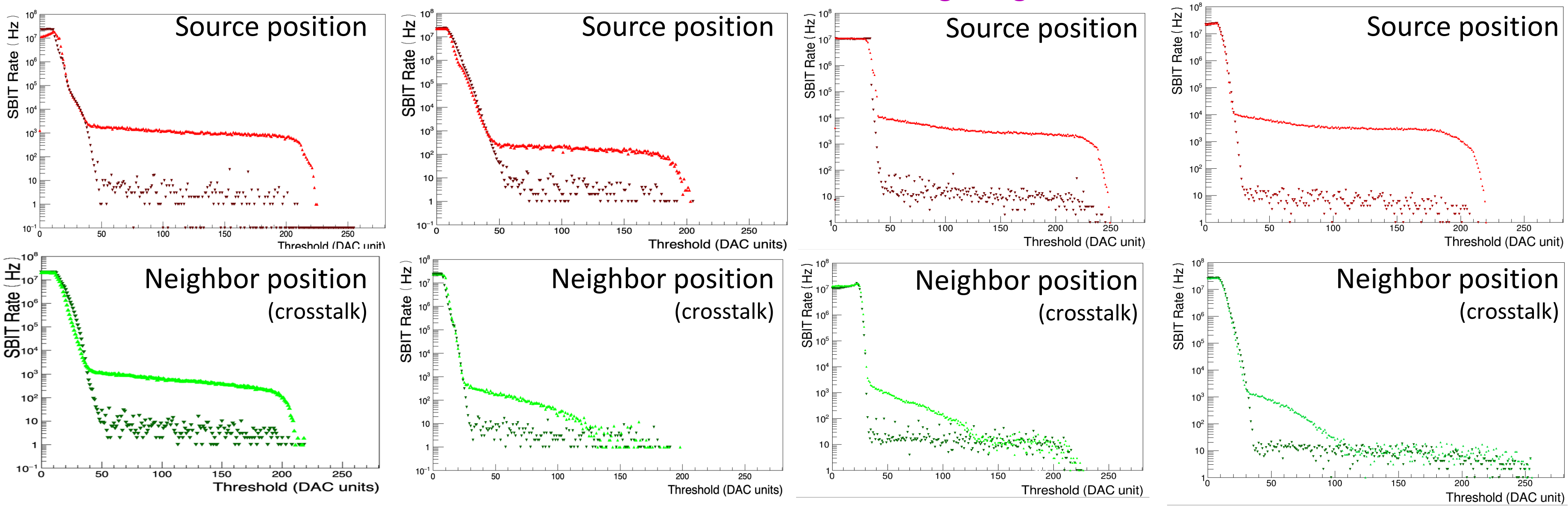


Combining the final design configuration and the new plugin cards do not affect the performance of the detectors nor the electronics

→ MIP efficiency reaches > 97 % in the expected operating range

Crosstalk Comparison

GE11 Double-segmented | GE11 with 10 merged HV | GE21 Single-segmented | GE21 Final "mixed" design



Lower amplitude but high probability at low thresholds

Two configurations with similar crosstalk behavior

- Both GE21 single-segmented and Mixed design show the same behavior in term of crosstalk probability and amplitude

→ confirmation that using segments with 0 Ω jumpers is **equivalent** to a unique electrode

Merging sectors in a double-segmented foil or using a single-segmented foil give the same crosstalk characteristics

→ **Clear improvement with respect to the fully double-segmented configuration**

Crosstalk Comparison (details)

Mixed design configuration:

Energy deposit = 351 ± 3 keV

	P_{XT}^{TH} : at fixed threshold (14 fC) (%)	P_{XT}^{Hz}: at nominal threshold (100 Hz noise) (%)
G = 4x10^4	3.5 ± 0.5	10.2 ± 0.7
G = 2x10^4	1.6 ± 1.8	10.7 ± 0.0 Most realistic
G = 1x10^4	0.12 ± 0.14	6.9 ± 0.2

Energy deposit = 124 ± 2 keV

	P_{XT}^{TH} : at fixed threshold (14 fC) (%)	P_{XT}^{Hz}: at nominal threshold (100 Hz noise) (%)
G = 4x10^4	0.9 ± 0.8	9.7 ± 3.6
G = 2x10^4	0.2 ± 0.0	5.9 ± 3.2 Most realistic
G = 1x10^4	0.0 ± 0.0	4.5 ± 3.1

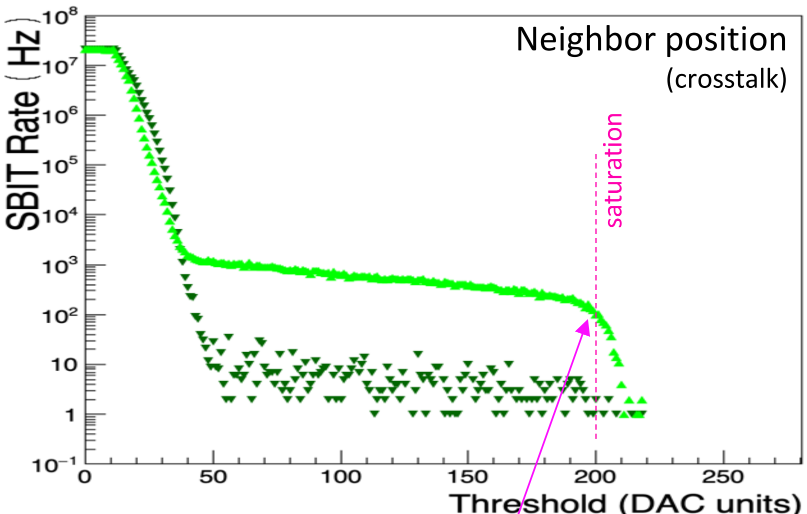
Double-segmented: 33.2 ± 3 % 86.8 ± 7 % 4.2 ± 0.7 % 43.4 ± 1.6 %

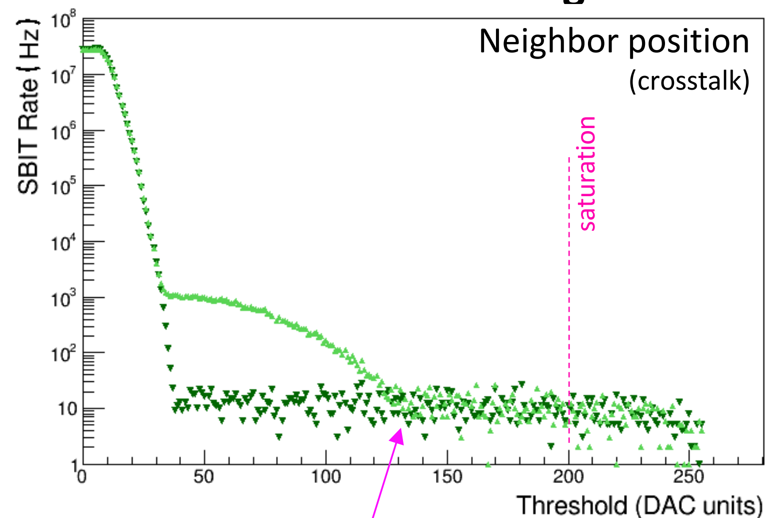
Confirmed once again that the crosstalk rate with X-rays is negligible, even at $G=4\times10^4$

P_{XT}^{TH}(Cd109)= 0.30 ± 0.29 %
P_{XT}^{Hz}(Cd109)= 0.22 ± 0.19 %
Within error bars

Crosstalk Comparison (details)

GE11 Double-segmented VS. **GE21 Final "mixed" design**





Flat rate up to 200 DAC units : saturation

→ Crosstalk signals are above the VFAT input range

→ Not possible to precisely evaluate the signal amplitude

Rate drop within the VFAT range

→ possibility to measure the maximum crosstalk amplitude

→ Possibility to precisely evaluate the electronics inoperative time and the crosstalk rate in P5

The crosstalk amplitude is reduced significantly with the mixed design

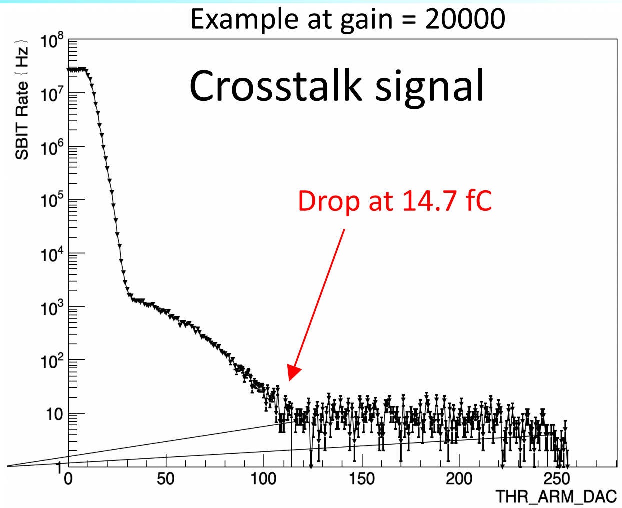
→ Possibility to precisely measure the signal characteristics and better evaluate the impact on the system performances

Crosstalk – Rate Estimations

Improving HIP rate estimation:

- The maximum crosstalk **amplitude** can be measured with the final mixed design
- Better estimation of the "**cross-talk generator**" candidates using the charge attenuation factor AF:
    - Typical operation threshold ~ 3.2 fC
    - Minimum charge to trigger crosstalk ~ 3.2 fC x AF
    - Then converted to keV released in the gas

→ **HIP threshold is set to 83.0 keV**



86.8 keV using data @ G=4x10^4
76.4 keV using data @ G=2x10^4
85.8 keV using data @ G=1x10^4

Charge Attenuation Factor

Alpha **average** signal charge:

C_α=40448 fC

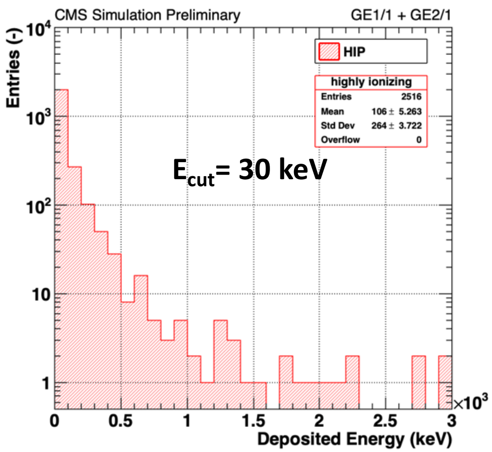
Crosstalk signal **max** charge:

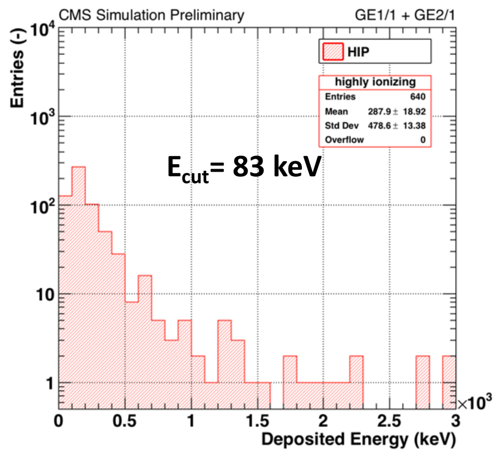
C_{XT}=14.7 fC

Attenuation factor:

AF > 2752

→ Conservative because comparing the max XT charge with the average alpha charge





Max crosstalk generator rate goes from 10.4 Hz/cm^2 to 3.7 Hz/cm^2

With a **better estimation** of the charge attenuation factor, the population of BKG particles susceptible to generate crosstalk is reduced by a **factor 2.8**

HL-LHC CMS

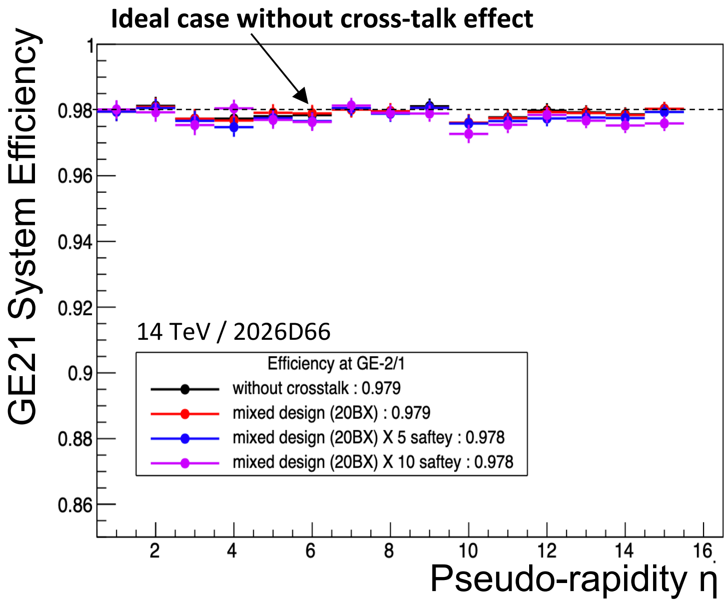
Final Mixed Design Solution

Note: all data were taken with an Alpha source releasing 351 ± 3 keV in the detector (*) Estimated values – not measurable due to the electronics saturation	Double-segmented design		Final Configuration (mixed design)
Discharge propagation probability at E_{ind}= 4.12 kV/cm	$\mathbf{Pd_{propa} < 10^{-4}}$	Same level of protection	$\mathbf{Pd_{propa} < 10^{-4}}$
Max rate of BKG particles capable of generating crosstalk (GE21)	10.4 Hz/cm^2 (*)	Improvement factor 2.8	3.7 Hz/cm^2
Crosstalk probability at G=2x10^4 at nominal threshold	86.8 ± 7.0 %	Improvement factor 8.1	10.7 ± 0.0 %
Fraction of the GE21 module affected by a crosstalk event (M1/M5 cases)	¼ of the module (1 eta partition)	Deterioration factor 4	Full module
Probability of channel activation during a crosstalk event	61 %	Similar behavior	52 %
Crosstalk-induced electronics dead time	50 BX (*)	Improvement factor 2.5	20 BX

<u>Toward the mixed design option:</u>

- The increase of the detector fraction affected by the crosstalk is extensively compensated by:
  - The reduction of the **BKG population** susceptible to trigger crosstalk
  - The reduction of the **probability** to observe crosstalk for this population
  - The minimizing of the electronics **dead time**

GE21 Final Design Validation



Simulation parameters:

- Event samples for Z → Mumu @ 14 TeV
- The **HIP rate** is estimated from the BKG simulation, convoluted with the crosstalk probability vs. **deposited energy** (> 83 keV).
- Each strip can possibly see the crosstalk from **the entire module**
- **Inoperative time** of **20 BX** based on the electronics simulation

First order approximation given by:

Probability of inactive RO per event : $P_{DT} = \frac{HIP_{rate}}{BX} \times Prob_{XT} \times InoperativeTime$

Rate Normalized to 1 BX

Then the real chamber efficiency is : $Eff_{real} = Eff_{ideal} \times (1 - P_{DT})$

The maximum **efficiency drop** due to the crosstalk effect is of the order of **0.04 %** at the highest eta (without safety factor)

→ **Successful mitigation**

Nota Bene

Some elements not considered in the calculations:

- The model considers that 100% of the strips in the range of the crosstalk are triggered
  → *Experimental data: 50 – 60 %*

- The charge attenuation factor used to calculate the HIP rate is derived from the comparison between the average HIP charge and the maximum crosstalk charge. The corresponding energy cut for HIP is 83 keV
  → *A new method to evaluate the attenuation factor indicates the actual HIP cut should be 138 keV (i.e. reduction of the HIP rate)*

- The model considers the worst case parameters for all modules (based on the M1/5 geometries)
  → *In reality the BKG population, the crosstalk probability, the inoperative time are significantly improved with the larger modules*

GEM Foil Production
- Brief Status Overview -

Impact on Production

Technical impact:

→ **No impact**: same foil layout as for the initial double-segmented design; the 100 kΩ on the bottom of GEM3 is simply replaced with a 0 Ω jumper with the same foot print

→ The other characteristics of the foils (base material, manufacturing process, cleaning) remain the same

→ The identification and labelling of GEM3 will be updated to highlight the difference with the other double segmented foils

Schedule impact:

→ The new schedule includes this additional R&D program and the corresponding updates on the production planning (reducing the float by a few months – detailed in spare slides)

→ The actual production plan includes more production sites than in the main schedule

- Possibility to increase the production rate

→ *The interruption caused by this R&D mostly overlaps with the interruption caused by the covid19 pandemic*

Final GE21foil configuration : based on the mixed design

→ **No technical impact on the production**

→ **Minor impact on the schedule, absorbed by the float**

→ **Possibility to recover delays by increasing the production rate**

Production Readiness

Production at CERN (M1/M5 and M4/M8)

→ Ready to start

→ Already produced 54 M5 and 19 M1 foils (before this new R&D)

- These foils can be re-used as GEM1 or GEM2 (same layout)
- The remaining M5 quantities will be equipped with the jumpers to define GEM3

Production at Mecaro (M2/M6 and M3/M7)

→ Fully approved at the GE21 EDR in May 2019 (presenting about 5 years of R&D for the technical validation of the company)

→ Production facility moved to a new location by the end of 2019 to increase the production capacity

→ Internal review organized in Jan 2020 in Korea with a visit of the factory

  → GEM experts gave suggestions to improve the production yield and speed

  → The company was supposed to produce new foils in order to validate the new facility and the optimization factors

  → Delayed due to the Covid

  → R&D foils are now in production and expected to be delivered by the end of Nov. 2020 for in-depth QC

→ Mecaro is expected to be fully ready for mass production in Dec. 2020

Conclusions

Design change from GE11 to GE21

→ Electronics degradation caused by the discharge propagation
→ Discharge propagation can be stopped using double-segmented foils

Crosstalk effect with the double-segmented foils

→ The bottom segmentation on GEM3 causes crosstalk on the facing RO strips
→ Crosstalk signals make the electronic inoperative for several tens of BX
→ Efficiency drop up to 1.4 % (no SF) at the highest eta
  → Need for an alternative solution

Crosstalk mitigation

→ Several options were investigated
→ Best result using single-segmented foils on the bottom of GEM3

Validation of the mixed design

→ Use the double-segmented design for GEM1/GEM2 and single-segmented for GEM3
→ Efficiency drop below to 0.4 % even with a SF 10
  → Good solution that fulfils all requirements (discharge, crosstalk, chamber performance)

Production status

→ CERN is ready to start
→ Mecaro is finalizing the production of new demonstrator foils
  → Expected to be ready for mass production in Dec. 2020

Thank you

Discharge Protection in GEMs

HIP with $E_{deposited} > 30$keV

P_d=1.24x10^{-9} ± 1.16x10^{-9}
(average of the two sets of tests we performed)
Measured with $E_{deposited}$ ~ 350 keV

Assuming a LHC duty cycle = 0.33

Factor based on the GEM foil design

Factor based on the RO circuitry

Factor based on the electronics protection circuit

Factor based on the optimization of the internal electric fields

System	Max HIP rate R_{HIP}^{max}	Disch. probability P_d	Max discharge rate R_d^{max}	Number of disch. per year	Transfer propagation probability	Induction propagation probability	Damage probability	Improvement factor (E_field optimization)	Number of damaged RO channels per 10 year	Fraction of damaged RO channels per 10 year
(Unit)	Hz/sector	-	Hz/sector	y^{-1}/sector	-	-	-	-	(10y)$^{-1}$	(10y)$^{-1}$ (%)
Slice test*	3.15x10^3	1.24x10^{-9}	3.90x10^{-6}	39	0.5	1	0.95	1	185 per VFAT(128 ch)	**100**
GE11	3.15x10^3	1.24x10^{-9}	3.90x10^{-6}	39	0.5	1	0.03	1	6 per VFAT	**4.79**
GE21	1.92x10^3	1.24x10^{-9}	2.38x10^{-6}	24	< 10^{-4}	< 10^{-3}	0.03	1	7x10^{-7} per VFAT	**~ 0**
ME0	2.36x10^5	1.24x10^{-9}	2.93x10^{-4}	2927	< 10^{-4}	< 10^{-3}	0.03	1	9x10^{-5} per VFAT	**~ 0**

*** Obsolete design – for comparison purpose**

Improved by the double-segmentation on GEM1 and GEM2

Improved by the de-coupling circuit on the plugin cards

Improved by VFAT protection resistor and the new HV filter config.

Studies are on-going: the improvement is not yet quantified

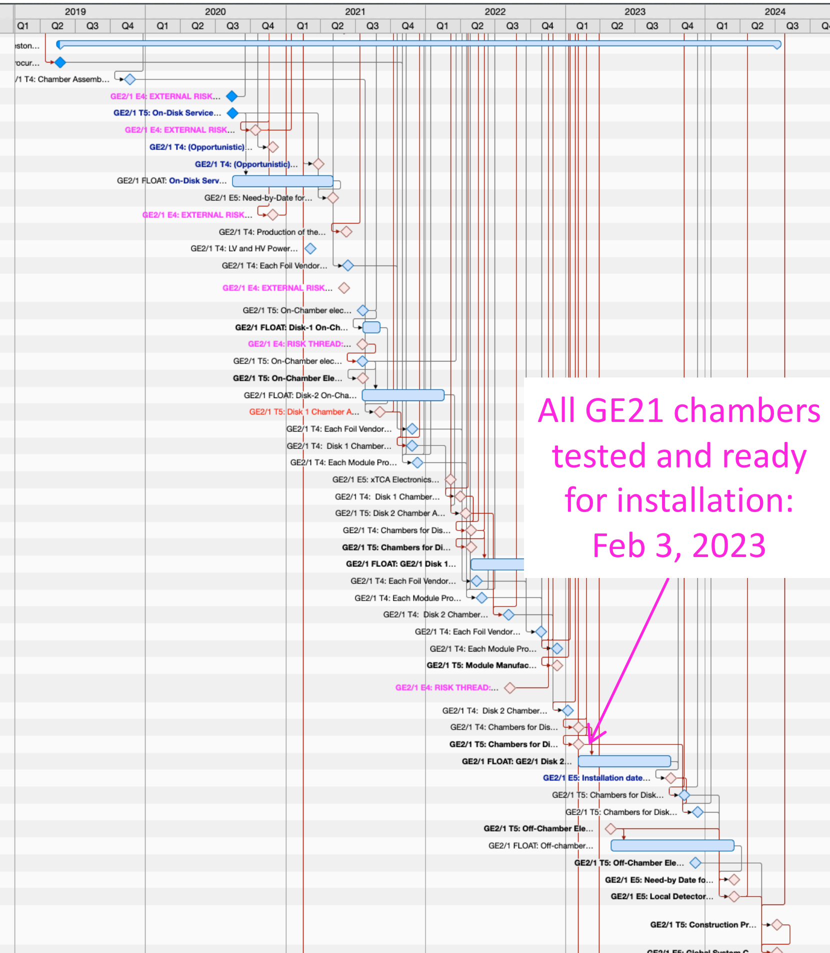
Note on the discharge rate:

- the table only takes into account discharges caused by incoming BKG particles
- Spontaneous discharges may occur at the beginning of the detector life due to the presence of dust and contaminants after the chamber movement/installation
    - A" **training procedure**" is in place to eliminate the dust and clean the foils in safe conditions

GE21 Construction: Forecast

- 4 months delay compared to baseline (float to need-by date is now 8 months)
  - Delay to the ESR has been largely mitigated by the PRR in July
  - Dominated by expected delays with PCBs due to funding availability in India (affected module production)
    - Assume that after the initial 64 module kits, we will have to wait until June 1, 2021 to resume production of the PCBs
  - Suspension of the foil production not on critical path only because of the delays with PCBs

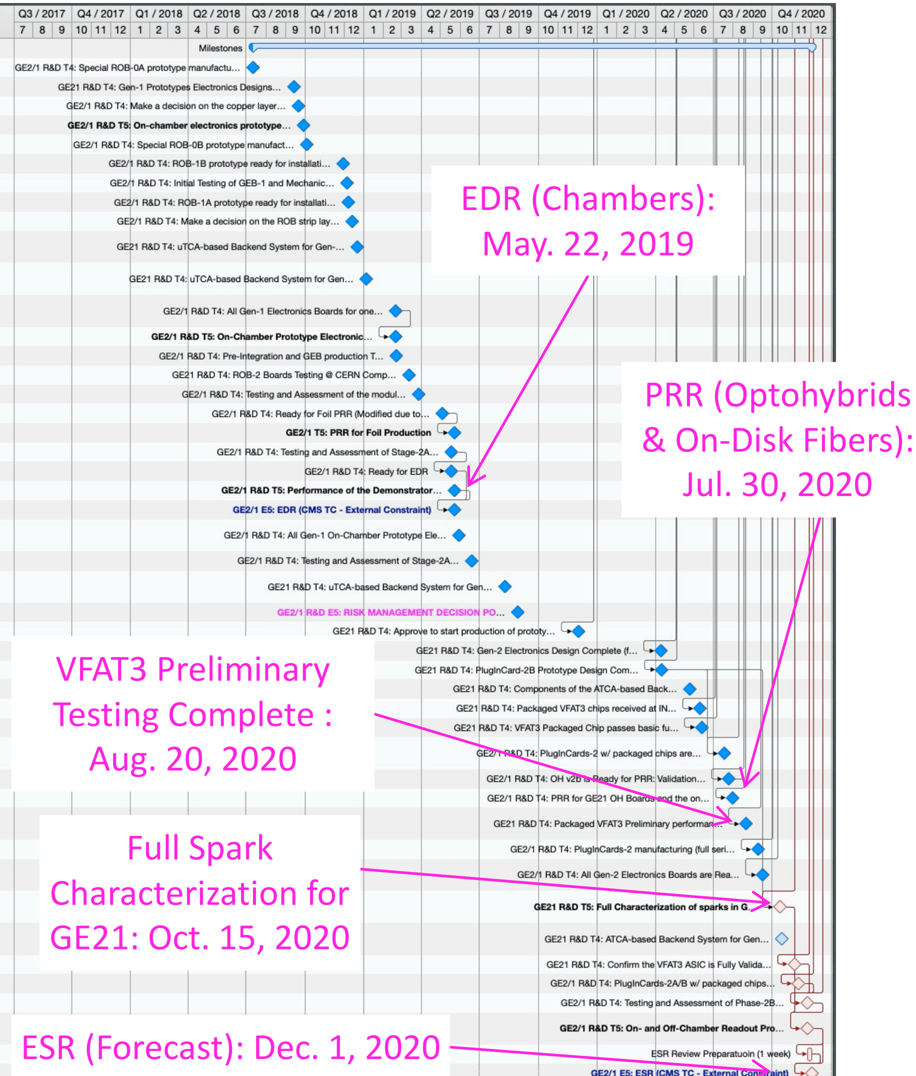
#	WBS Code	Title	Master Schedule reference	Expected End
1,575	2.5.2.10.421	**GE2/1 Construction Milestones**		**July 5, 2024**
1,576	2.5.2.10.421.438	GE2/1 T4: Start of the Procurements for Module Production		May 23, 2019
1,577	2.5.2.10.421.463	GE2/1 T4: Chamber Assembly Components and Setup are Ready to Start Chamber Assembly		Nov 20, 2019
1,578	2.5.2.10.421.454	**GE2/1 E4: EXTERNAL RISK THREAD: GE21 (At Least Partial) Funding Availabie for GE21 Module PCBs Used in GE21 Module Assembly**		Aug 12, 2020
1,579	2.5.2.10.421.450	**GE2/1 T5: On-Disk Services Installation (excludes fibers) at P5 is Complete**	GE21.PR.DET.1	Aug 14, 2020
1,580	2.5.2.10.421.420	**GE2/1 E4: EXTERNAL RISK THREAD: GE21 Foil Production at CERN Can Re-Start (following cross-talk R&D)**		Oct 13, 2020
1,581	2.5.2.10.421.450	**GE2/1 T4: (Opportunistic) On-Disk Fibers Installation at P5 is Complete for Endcap-1**		Nov 27, 2020
1,582	2.5.2.10.421.450	**GE2/1 T4: (Opportunistic) On-Disk Fibers Installation at P5 is Complete for Endcap-2**		Mar 26, 2021
1,583	2.5.2.10.421.468	GE2/1 FLOAT: **On-Disk Services Installation to NEED-BY-DATE**		May 3, 2021
1,584	2.5.2.10.421.467	GE2/1 E5: Need-by-Date for Services Installation Completion (Assume end of LS2)		May 3, 2021
1,585	2.5.2.10.421.420	**GE2/1 E4: EXTERNAL RISK THREAD: Mecaro GE21 Foil Production Start Delayed (date that procurements can start)**		Nov 27, 2020
1,586	2.5.2.10.421.464	GE2/1 T4: Production of the First GE2/1 Module Has Started		June 8, 2021
1,587	2.5.2.10.421.429	GE2/1 T4: LV and HV Power Supply Pre-Series modules tested and validated		March 5, 2021
1,588	2.5.2.10.421.441	GE2/1 T4: Each Foil Vendor Delivers 25% of Foils Assigned		June 11, 2021
1,589	2.5.2.10.421.454	**GE2/1 E4: EXTERNAL RISK THREAD: Re-start production of PCBs used in module asssembly beyond the initial batch (depends on funding availability)**		June 1, 2021
1,590	2.5.2.10.421.451	GE2/1 T5: On-Chamber electronics components ready for Disk-1 Chamber Assembly		July 20, 2021
1,591	2.5.2.10.421.445	**GE2/1 FLOAT: Disk-1 On-Chamber Electronics Components Ready for Installation to NEED-BY date**		Sep 3, 2021
1,592	2.5.2.10.421.420	**GE2/1 E4: RISK THREAD: GE21 On-Chamber Electronics: Delivery of the Last Component Delayed (date the component finally becomes available)**		July 20, 2021
1,593	2.5.2.10.421.435	GE2/1 T5: On-Chamber electronics components ready for Disk-2 Chamber Assembly		July 20, 2021
1,594	2.5.2.10.421.447	**GE2/1 T5: On-Chamber Electronics Manufacturing and Testing is Completed**	GE21.PR.FE.1	July 20, 2021
1,595	2.5.2.10.421.459	GE2/1 FLOAT: Disk-2 On-Chamber Electronics Components Ready for Installation to NEED-BY date		Feb 18, 2022
1,596	2.5.2.10.421.443	GE2/1 T5: Disk 1 Chamber Assembly Starts (DRIVEN BY RESOURCE AVAILABILITY DUE TO GE11 Commissionning])		Sep 3, 2021
1,597	2.5.2.10.421.456	GE2/1 T4: Each Foil Vendor Delivers 50% of Foils Assigned		Nov 26, 2021
1,598	2.5.2.10.421.452	GE2/1 T4: Disk 1 Chamber Assembly 50% Completed		Nov 26, 2021
1,599	2.5.2.10.421.448	GE2/1 T4: Each Module Production Site Delivers 33% of Modules Assigned		Dec 10, 2021
1,600	2.5.2.10.421.444	GE2/1 E5: xTCA Electronics Available for Ordering (External Constraint)		March 7, 2022
1,601	2.5.2.10.421.436	GE2/1 T4: Disk 1 Chamber Assembly 100% Completed		April 1, 2022
1,602	2.5.2.10.421.425	GE2/1 T5: Disk 2 Chamber Assembly Starts		April 15, 2022
1,603	2.5.2.10.421.442	GE2/1 T4: Chambers for Disk 1 Produced, Tested and Certified, ready for installation. Ready to start testing and certification of chambers for Disk-2.		April 29, 2022
1,604	2.5.2.10.421.426	**GE2/1 T5: Chambers for Disk-1 are Assembled, Tested, and Ready for Installation**	GE21.PR.DET.2	April 29, 2022
1,605	2.5.2.10.421.445	**GE2/1 FLOAT: GE2/1 Disk 1 Ready for Installation to TC Installation Start Date**		Oct 2, 2023
1,606	2.5.2.10.421.428	GE2/1 T4: Each Foil Vendor Delivers 75% of Foils Assigned		May 13, 2022
1,607	2.5.2.10.421.434	GE2/1 T4: Each Module Production Site Delivers 66% of Modules Assigned		May 27, 2022
1,608	2.5.2.10.421.457	GE2/1 T4: Disk 2 Chamber Assembly 50% Completed		August 5, 2022
1,609	2.5.2.10.421.439	GE2/1 T4: Each Foil Vendor Delivers 100% of Foils Assigned		Oct 28, 2022
1,610	2.5.2.10.421.432	GE2/1 T4: Each Module Production Site Delivers 100% of Modules Assigned		Dec 9, 2022
1,611	2.5.2.10.421.460	**GE2/1 T5: Module Manufacturing and Testing is Complete**	GE21.PR.DET.3	Dec 9, 2022
1,612	2.5.2.10.421.420	**GE2/1 E4: RISK THREAD: GE21 Module Manufacturing Completion Delayed (date the manufacturing is completed so the testing of the last batch of modules can start in prep for assembly)**		August 9, 2022
1,613	2.5.2.10.421.433	GE2/1 T4: Disk 2 Chamber Assembly 100% Completed		Jan 6, 2023
1,614	2.5.2.10.421.423	GE2/1 T4: Chambers for Disk 2 Produced, Tested and Certified, ready for installation		Feb 3, 2023
1,615	2.5.2.10.421.427	**GE2/1 T5: Chambers for Disk-2 are Assembled, tested, and Ready for Installation**	GE21.PR.DET.4	Feb 3, 2023
1,616	2.5.2.10.421.446	**GE2/1 FLOAT: GE2/1 Disk 2 Ready for Installation to TC Installation Start Date**		Oct 2, 2023
1,617	2.5.2.10.421.449	**GE2/1 E5: Installation date agreed upon with TC (2020 schedule update)**		Oct 2, 2023
1,618	2.5.2.10.421.437	GE2/1 T5: Chambers for Disk-1 Installed and Tested		Nov 6, 2023
1,619	2.5.2.10.421.430	GE2/1 T5: Chambers for Disk-2 Installed and Tested		Dec 11, 2023
1,620	2.5.2.10.421.421	**GE2/1 T5: Off-Chamber Electronics Manufacturing and Testing Completed and Ready for Installation**	GE21.PR.BE.1	April 28, 2023
1,621	2.5.2.10.421.466	GE2/1 FLOAT: Off-chamber electronics ready for installation to need-by date		Mar 15, 2024
1,622	2.5.2.10.421.453	**GE2/1 T5: Off-Chamber Electronics Integration Complete**	GE21.PR.BE.2	Dec 5, 2023
1,623	2.5.2.10.421.455	**GE2/1 E5: Need-by Date for Off-Chamber Electronics (Local Detector Commissionning Starts)**		Mar 15, 2024
1,624	2.5.2.10.421.455	**GE2/1 E5: Local Detector Commissionning Starts (External Constraint)**		Mar 15, 2024
1,625	2.5.2.10.421.431	**GE2/1 T5: Construction Project Complete. Ready for Global System Commissionning.**	GE21.PR.DET5 GE21.PR.FE.2 GE21.PR.BE.3	July 5, 2024
1,626	2.5.2.10.421.424	**GE2/1 E5: Global System Commissionning Starts (External Constraint)**		July 5, 2024



GE21 R&D Schedule: Forecast

- The ATCA backend processor selection to be factorized out of the ESR into a separate PRR
  - None of the target CMS ATCA processor boards designs in the pre-production stage yet

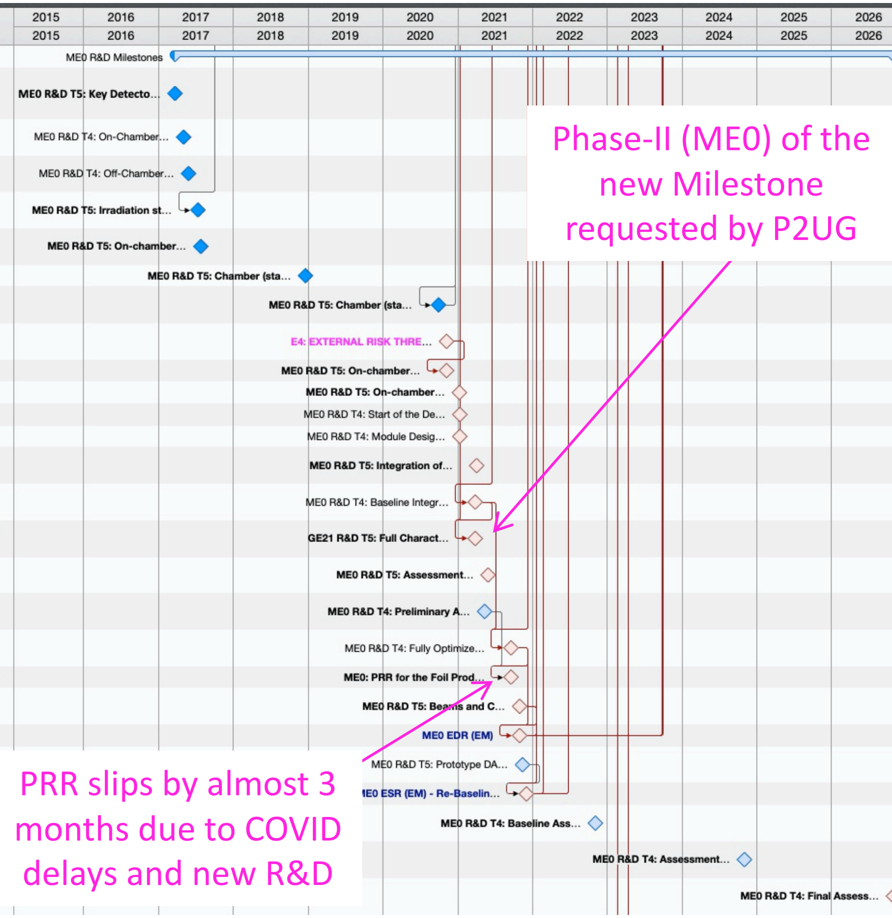
#	WBS Code	Title	Master Schedule reference	Expected End
712	**5**	▼ **Milestones**		**Dec 1, 2020**
713	5.1	GE2/1 R&D T4: Special ROB-0A prototype manufactured and ready for installation on chamber		July 11, 2018
714	5.2	GE21 R&D T4: Gen-1 Prototypes Electronics Designs Complete, Ready for Project Level Review		Sep 13, 2018
715	5.3	GE2/1 R&D T4: Make a decision on the copper layer on ROB		Sep 20, 2018
716	115	**GE2/1 R&D T5: On-chamber electronics prototypes engineering design complete**	GE21.RD.FE.3	Sep 28, 2018
717	5.5	GE2/1 R&D T4: Special ROB-0B prototype manufactured and ready for installation on chamber		Oct 4, 2018
718	5.6	GE2/1 R&D T4: ROB-1B prototype ready for installation on the demonstrator chamber		Nov 29, 2018
719	5.7	GE2/1 R&D T4: Initial Testing of GEB-1 and Mechanical Integration Validation Complete		Dec 5, 2018
720	5.8	GE2/1 R&D T4: ROB-1A prototype ready for installation on the demonstrator chamber		Dec 7, 2018
721	5.9	GE2/1 R&D T4: Make a decision on the ROB strip layout configuration		Dec 13, 2018
722	5.10	GE21 R&D T4: uTCA-based Backend System for Gen-1/2 GE21 electronics is Ready for Trial Integration with Gen-1 on-Chamber Electronics and Preliminary Measurements of Noise with Stage-1 Demonstrator		Dec 21, 2018
723	5.11	GE21 R&D T4: uTCA-based Backend System for Gen-1/2 GE21 electronics is Ready for Full Integration Testing with Gen-1 on-Chamber Electronics		Jan 4, 2019
724	5.12	GE2/1 R&D T4: All Gen-1 Electronics Boards for one module are ready for mechanical integration assessment with the Stage-1 Demonstrator @ CERN		Feb 19, 2019
725	130	**GE2/1 R&D T5: On-Chamber Prototype Electronics Manufacturing and Testing is Complete [At least One Full Module]**	GE21.RD.FE.4	Feb 19, 2019
726	5.14	GE2/1 R&D T4: Pre-Integration and GEB production Test-stand @ PKU Complete		Feb 20, 2019
727	5.15	GE21 R&D T4: ROB-2 Boards Testing @ CERN Completed		Mar 12, 2019
728	5.16	GE2/1 R&D T4: Testing and Assessment of the modules for Stage-2A Demonstrator w/ APV electronics Complete		Mar 27, 2019
729	5.17	GE2/1 R&D T4: Ready for Foil PRR (Modified due to GE21-002 Change Control)		May 3, 2019
730	140	**GE2/1 T5: PRR for Foil Production**		May 22, 2019
731	5.19	GE2/1 R&D T4: Testing and Assessment of Stage-2A Demonstrator (partial: GEB M1-2) w/ Gen-1 electronics Complete		May 17, 2019
732	5.20	GE2/1 R&D T4: Ready for EDR		May 17, 2019
733	160	**GE2/1 R&D T5: Performance of the Demonstrator chamber with Prototype Electronics is Validated**	GE21.RD.DET.4	May 22, 2019
734	170	**GE2/1 E5: EDR (CMS TC - External Constraint)**		May 22, 2019
735	5.23	GE2/1 R&D T4: All Gen-1 On-Chamber Prototype Electronics Manufacturing and Testing is Complete. Ready for full integration with the Stage-2A Demonstrator @ CERN.		May 29, 2019
736	5.24	GE2/1 R&D T4: Testing and Assessment of Stage-2A Demonstrator w/ Gen-1 electronics Complete		Jun 18, 2019
737	5.25	GE21 R&D T4: uTCA-based Backend System for Gen-2 GE21 electronics is Ready for Full Integration Testing with Gen-2 on-Chamber Electronics		Aug 9, 2019
738	5.26	**GE2/1 R&D E5: RISK MANAGEMENT DECISION POINT: GBTX-based readout selected for ESR**		Aug 30, 2019
739	5.27	GE21 R&D T4: Approve to start production of prototype packaged VFAT3 chips		Dec 2, 2019
740	5.28	GE21 R&D T4: Gen-2 Electronics Design Complete (for two chambers w/ full LpGBT capabilities); Ready for Manufacturing		Apr 10, 2020
741	5.29	GE21 R&D T4: PlugInCard-2B Prototype Design Complete (includes VFAT3 protection), Ready for Production		Apr 10, 2020
742	5.30	GE21 R&D T4: Components of the ATCA-based Backend Readout System Hardware Test-Stand are Ready for Integration		May 25, 2020
743	5.31	GE21 R&D T4: Packaged VFAT3 chips received at INFN Bari		June 9, 2020
744	5.32	GE21 R&D T4: VFAT3 Packaged Chip passes basic functionality tests		Jun 12, 2020
745	5.33	GE2/1 R&D T4: PlugInCards-2 w/ packaged chips are tested and ready for mechanical integration and perfomance studies @ CERN		July 17, 2020
746	5.34	GE2/1 R&D T4: OH v2b is Ready for PRR: Validation with packaged VFAT3 & PlugInCards-2 at RICE is complete		July 24, 2020
747	5.35	GE2/1 R&D T4: PRR for GE21 OH Boards and the on-disk part of the optical fiber system		July 30, 2020
748	5.36	GE21 R&D T4: Packaged VFAT3 Preliminary performance testing and packaging validation at INFN/Bari completed (some tests not fully completed due to testing hardware tools requiring tuning)		Aug 20, 2020
749	5.37	GE2/1 R&D T4: PlugInCards-2 manufacturing (full series) starts at a European vendor		Sep 8, 2020
750	5.38	GE2/1 R&D T4: All Gen-2 Electronics Boards are Ready for Installation on Stage-2B Demonstrator and mechanical integration studies @ CERN (w/ a limited number of new plug-in cards)		Sep 15, 2020
751	5.39	**GE21 R&D T5: Full Characterization of sparks in GEMs (a new milestone requested by P2UG) - [a full final operational configuration validated for GE21, ME0 configuration will likely require separate validation]**		Oct 13, 2020
752	5.40	GE21 R&D T4: ATCA-based Backend System for Gen-2/3 GE21 electronics is Ready for Full Integration Testing with Gen-3 on-Chamber Electronics		Oct 15, 2020
753	5.41	GE21 R&D T4: Confirm the VFAT3 ASIC is Fully Validated for GE21 (incl. forward compatibiulity w/ LpGBT)		Nov 4, 2020
754	5.42	GE2/1 R&D T4: PlugInCards-2A/B w/ packaged chips and updated chip protection are tested and ready		Nov 10, 2020
755	5.43	GE2/1 R&D T4: Testing and Assessment of Phase-2B Demonstrator w/ Gen-2 electronics Complete		Nov 24, 2020
756	190	**GE2/1 R&D T5: On- and Off-Chamber Readout Prototype Electronics Integration and Performance Studies Completed**	GE21.RD.FE.5 GE21.RD.BE.3	Nov 24, 2020
757	5.45	ESR Review Preparatuoin (1 week)		Dec 1, 2020
758	200	**GE2/1 E5: ESR (CMS TC - External Constraint)**		Dec 1, 2020



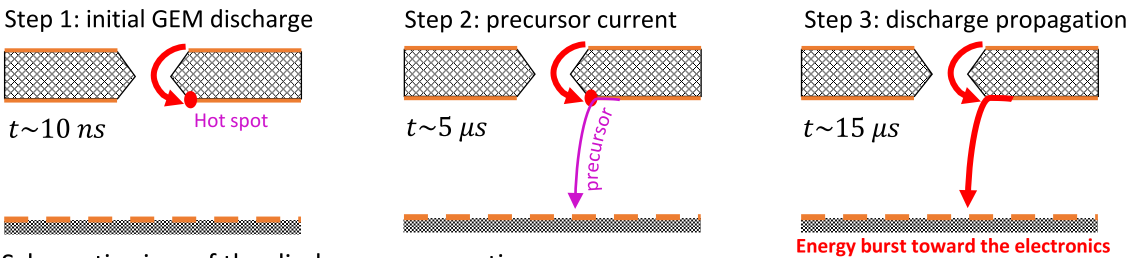
MEO R&D Schedule: Forecast

- Includes additional R&D for design optimization aimed at improved rate capabilities and discharge protection
  - Essential in light of more stringent requirements c.f. TDR
  - PRR for the foils slips by ~3 months (can merge with the EDR)
  - As of now, EDR and ESR are still projected on time
    - A large increase in the density of activities makes schedule risks significant and additional delays likely

#	WBS Code	Title	Master Schedule reference	Expected End
2,453	2.5.3.10.501	▼ ME0 R&D Milestones		Oct 29, 2026
2,454	2.5.3.10.501.424	ME0 R&D T5: Key Detector System Design Parameters Are Defined Based on Performance Requirements	ME0.RD.DET.1 ME0.RD.FE.1 ME0.RD.BE1	Mar 21, 2017
2,455	2.5.3.10.501.431	ME0 R&D T4: On-Chamber Electronics Preliminary Principal Design Complete and Specs Defined (HM)		May 2, 2017
2,456	2.5.3.10.501.425	ME0 R&D T4: Off-Chamber Electronics Preliminary Principal Design Complete and Specs Defined (HM)		May 26, 2017
2,457	2.5.3.10.501.427	ME0 R&D T5: Irradiation studies and assessment of performance and longevity with small prototypes completed	ME0.RD.DET.2	July 11, 2017
2,458	2.5.3.10.501.430	ME0 R&D T5: On-chamber & off-chamber electronics preliminary principal design complete and interfaces defined	ME0.RD.FE.2 ME0.RD.BE.2	July 25, 2017
2,459	2.5.3.10.501.434	ME0 R&D T5: Chamber (stack) prototype mechanical design completed	ME0.RD.DET.3	Dec 18, 2018
2,460	2.5.3.10.501.437	ME0 R&D T5: Chamber (stack) prototype mechanical prototype testing and validation complete	ME0.RD.DET.4	Sep 29, 2020
2,461	2.5.3.10.501.432	E4: EXTERNAL RISK THREAD: Delay due to packaged VFAT3 production/validation completion (COMES FROM THE VFAT3 VALIDATION SCHEDULE)		Nov 6, 2020
2,462	2.5.3.10.501.433	ME0 R&D T5: On-chamber electronics engineering design completed and validated	ME0.RD.FE.3	Nov 6, 2020
2,463	2.5.3.10.501.435	ME0 R&D T5: On-chamber prototype electronics manufacturing and testing complete	ME0.RD.FE.4	Jan 8, 2021
2,464	2.5.3.10.501.426	ME0 R&D T4: Start of the Demonstrator Module Assembly with Prototype Electronics		Jan 11, 2021
2,465	2.5.3.10.501.426	ME0 R&D T4: Module Design Baseline for Rate Studies is Established		Jan 11, 2021
2,466	2.5.3.10.501.438	ME0 R&D T5: Integration of the on-chamber and off-chamber electronics and performance assessment completed	ME0.RD.BE.3	April 2, 2021
2,467	2.5.3.10.501.5	ME0 R&D T4: Baseline Integrated Design with Improved Rate/Discharge Capabilities Validated and Complete		Mar 26, 2021
2,468	2.5.3.10.501.440	GE21 R&D T5: Full Characterization of sparks in GEMs (a new milestone requested by P2UG) Phase-II (ME0)		Mar 26, 2021
2,469	2.5.3.10.501.422	ME0 R&D T5: Assessment of the electronics performance and integration with the demonstrator chamber completed	ME0.RD.DET.5 ME0.RD.FE.5	May 28, 2021
2,470	2.5.3.10.501.423	ME0 R&D T4: Preliminary Assessment of the Modules Aging Capabilities (HL-LHC safety factor over 0.25)		May 12, 2021
2,471	2.5.3.10.501.5	ME0 R&D T4: Fully Optimized Integrated Design with Improved Rate/Discharge Capabilities Validated and Complete		Sep 17, 2021
2,472	2.5.3.10.501.423	ME0: PRR for the Foil Production		Sep 17, 2021
2,473	2.5.3.10.501.436	ME0 R&D T5: Beams and Cosmics testing of the demonstrator chamber and performance qualification completed; Ready for EDR	ME0.RD.DET.6	Oct 29, 2021
2,474	2.5.3.10.501.439	ME0 EDR (EM)		Oct 29, 2021
2,475	2.5.3.10.501.428	ME0 R&D T5: Prototype DAQ Electronics Testing and Integration as part of the ME0 Demonstrator Complete. ready for ESR		Nov 12, 2021
2,476	2.5.3.10.501.429	ME0 ESR (EM) - Re-Baseline from 27.Apr.2021 to 01.Dec.2021		Dec 1, 2021
2,477	2.5.3.10.501.423	ME0 R&D T4: Baseline Assessment of the Modules Aging Capabilities (HL-LHC safety factor over 1.0)		Nov 3, 2022
2,478	2.5.3.10.501.423	ME0 R&D T4: Assessment of the Modules Aging Capabilities (HL-LHC safety factor over 2.0)		Oct 31, 2024
2,479	2.5.3.10.501.423	ME0 R&D T4: Final Assessment of the Modules Aging Capabilities (HL-LHC safety factor over 3.0)		Oct 29, 2026



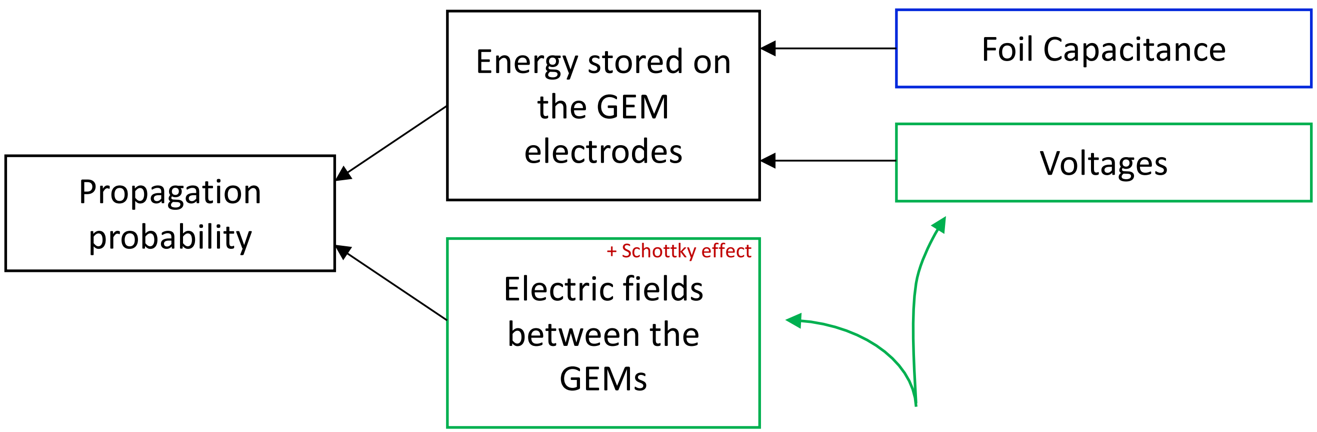
Mitigation Strategies – Propagation Prob.



Schematic view of the discharge propagation process

Basic principle:

Regular GEM discharges can heat up the copper rim of GEM holes and provoke the thermionic emission of electrons in the gas (precursor current). If the energy is sufficient, the precursor current grows and become a streamer (secondary discharge in the gaps)



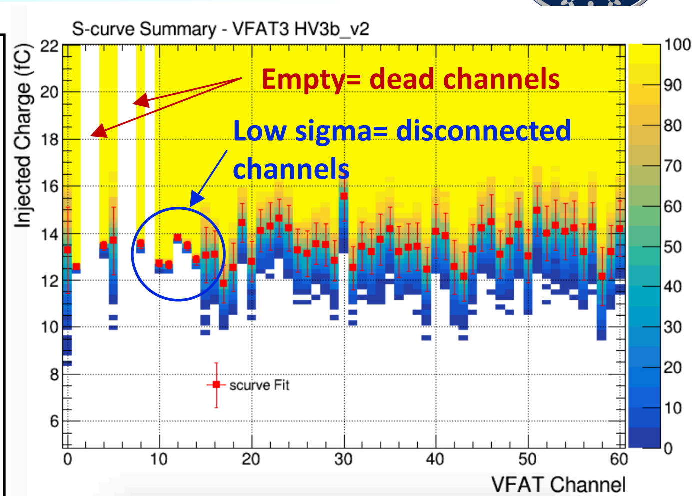
1st order mitigation:
- Double-segmented foils

2nd order mitigations:
- **Optimized electric field configuration**
- **AC-coupled readout with drain resistor**

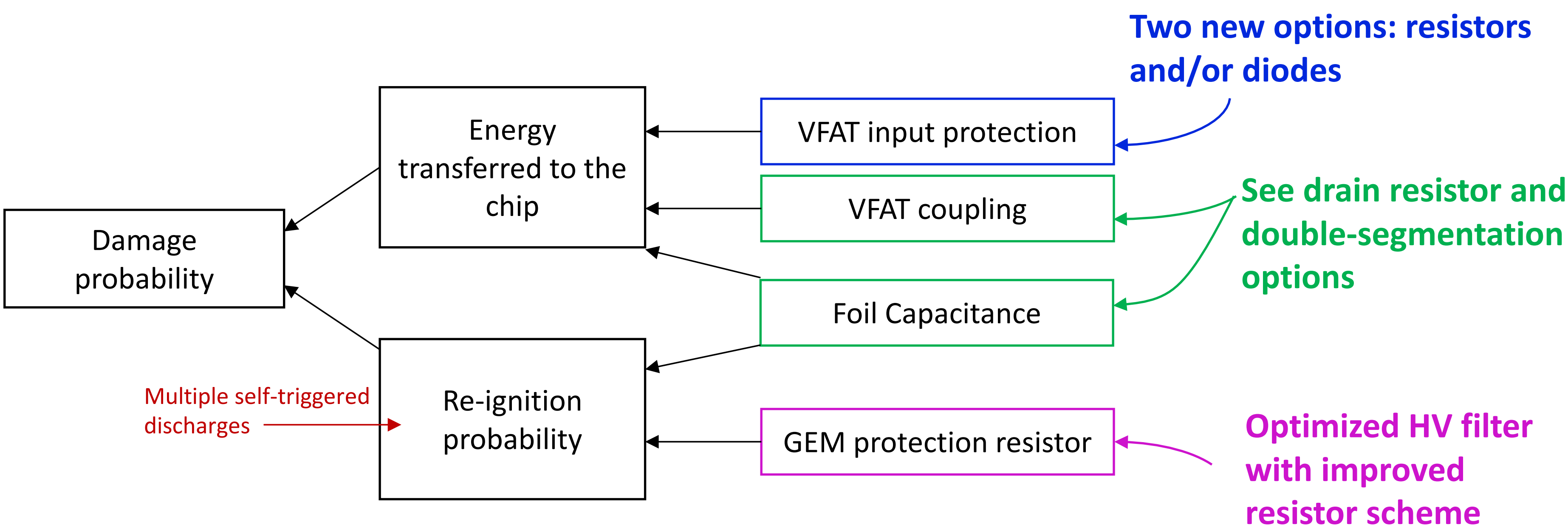
Mitigation Strategies – Damage Prob.

Three main damage processes are identified:

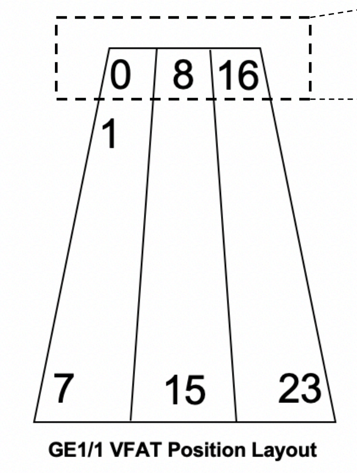
1. Full discharge energy **burns** vital components → dead channel, not responding
2. The discharge energy **melts** the bonding wire → disconnected channel, low noise profile
3. *The discharge current runs through the ground line and induce a ΔV with the power line → the entire chip becomes non functional (very rare case, only possible when using protection diodes)*



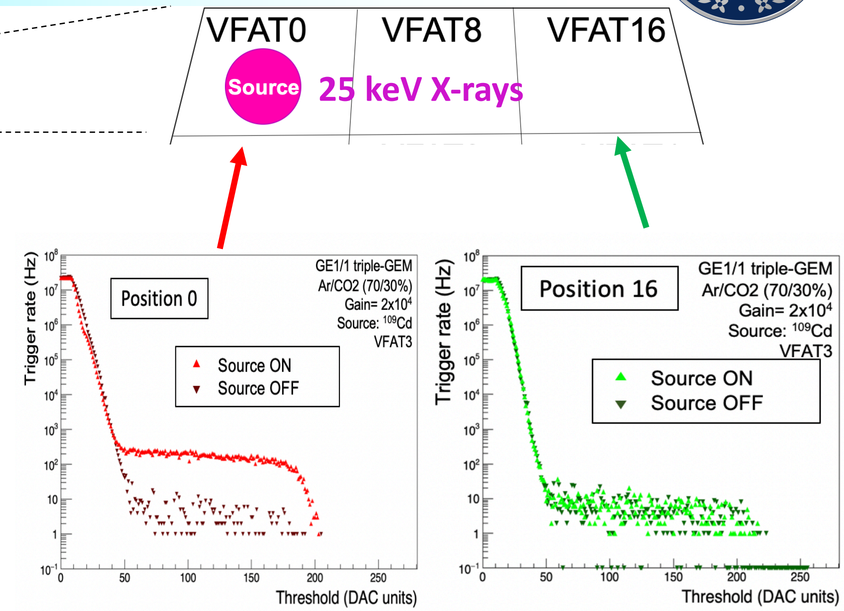
Typical VFAT damage profile after a discharge

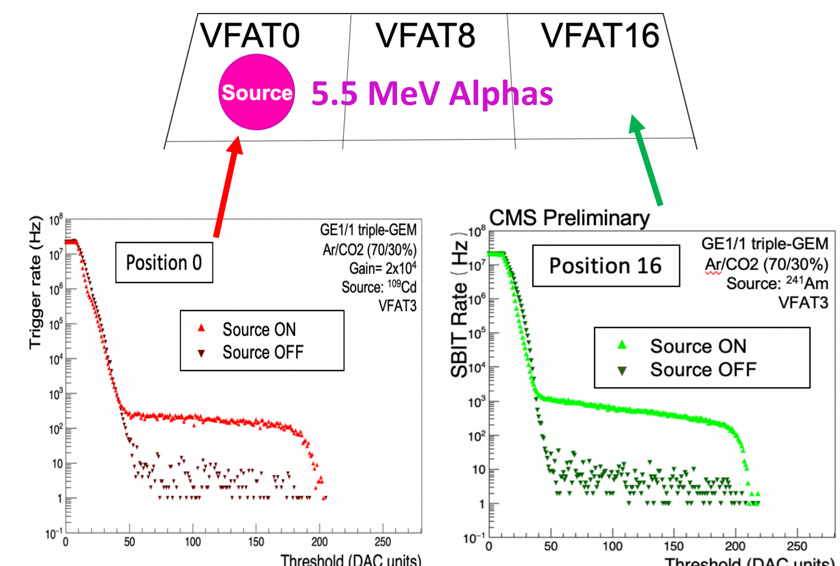


Crosstalk - Probability



GE1/1 VFAT Position Layout





Cross-talk definition:

- Parasitic signals induced on electronics channels in the neighborhood of the particle hit
- Signal of opposite polarity with respect to the original “good” signal
- In case of large amplitude, the mirror signal undershoot can trigger the electronics
- Not observable with X-rays or lower energy events
- Clearly visible with alphas particles

Mitigation Strategies Overview

Additional limitation (chambers already assembled when the mitigation strategies were developed)

GE11 System

- Re-design of the HV filter
- Re-design of the VFAT3 input protection

→ **New protocols to clean the foils before real operation (already implemented at the level of the QC, the cosmic test and during in the P5 commissioning phase**

→ **New operating configurations – work in progress**

Also propagated to GE21 and ME0

Similar environment and similar constraints

GE21 System

- AC-coupling the RO electronics and use of drain resistors
- Double-segmentation of the GEM foils (mixed design)

→ **A final prototype was assembled with all final design elements for a final integration validation**

Possibility to work at design level and implement more efficient solutions

More complex environment with additional constraints

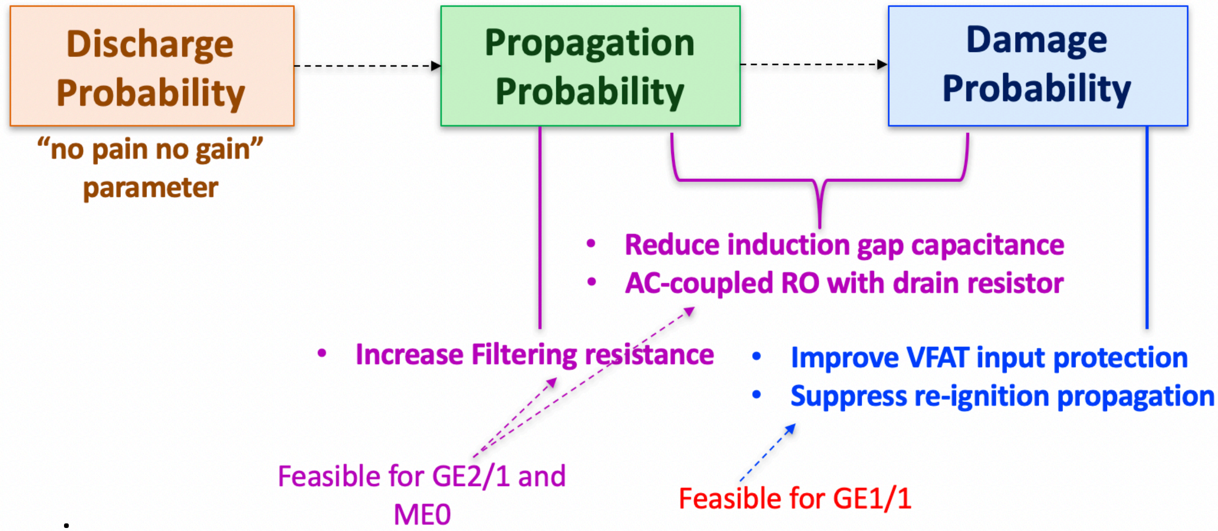
ME0 System

- The baseline: based on the protections introduced for GE2/1
- **However, the parameters for the discharge protections elements must be fine tuned to cope with the large BKG rate expected in the ME0 forward region → on-going R&D**

Discharge mitigation in GE11

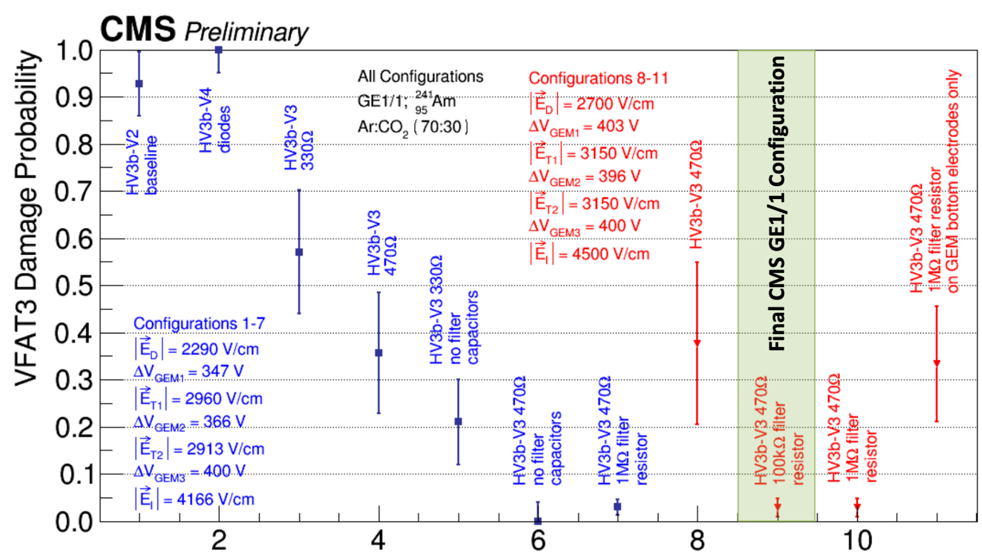
Discharge propagation mitigation:

- Four main hardware options we highlighted by the discharge study
- Acting on both propagation probability and damage probability



→ For GE1/1: limited HW options since the chambers were already assembled (cannot act at the design level)

- ❖ HW options: reinforce the VFAT3 protection circuit; Reduce the energy available in the HV line (discharge re-ignition)
- ❖ Operational options: optimize the E field configuration to reduce the propagation probability (on-going)



ME0 Problematics

Background rates in the ME0 environment:

- Expected BKG rate up to 150 kHz/cm^2
- HIP rates up to 4 kHz/cm^2

→ Imposes the use of robust protections against discharge propagation (at least equivalent to the GE2/1 case)

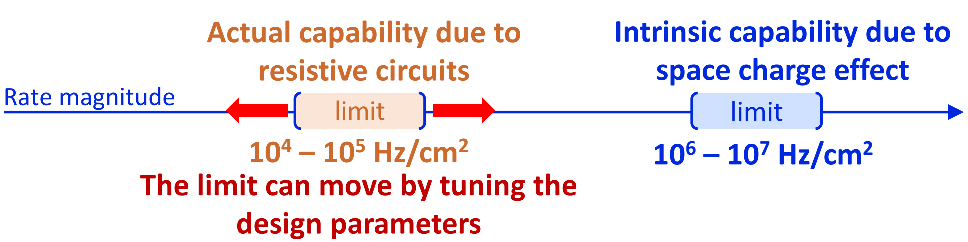
Update of the BKG simulation:

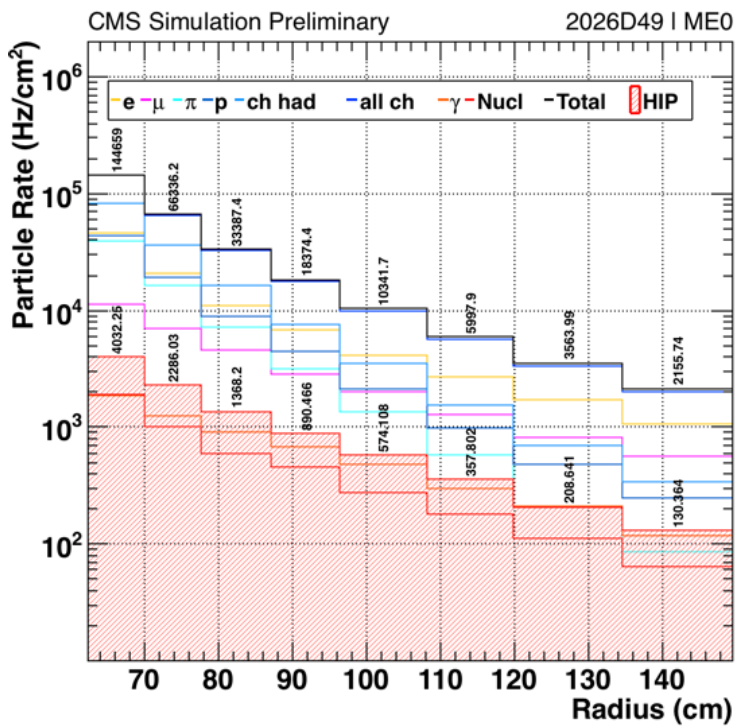
- Prompt BKG not included in the TDR summary Tables
- Update of the simulations using latest HGCAL & CMS Phase-2 geometry

→ Higher rate with respect to the first TDR estimation

Rate Capability in the ME0 environment:

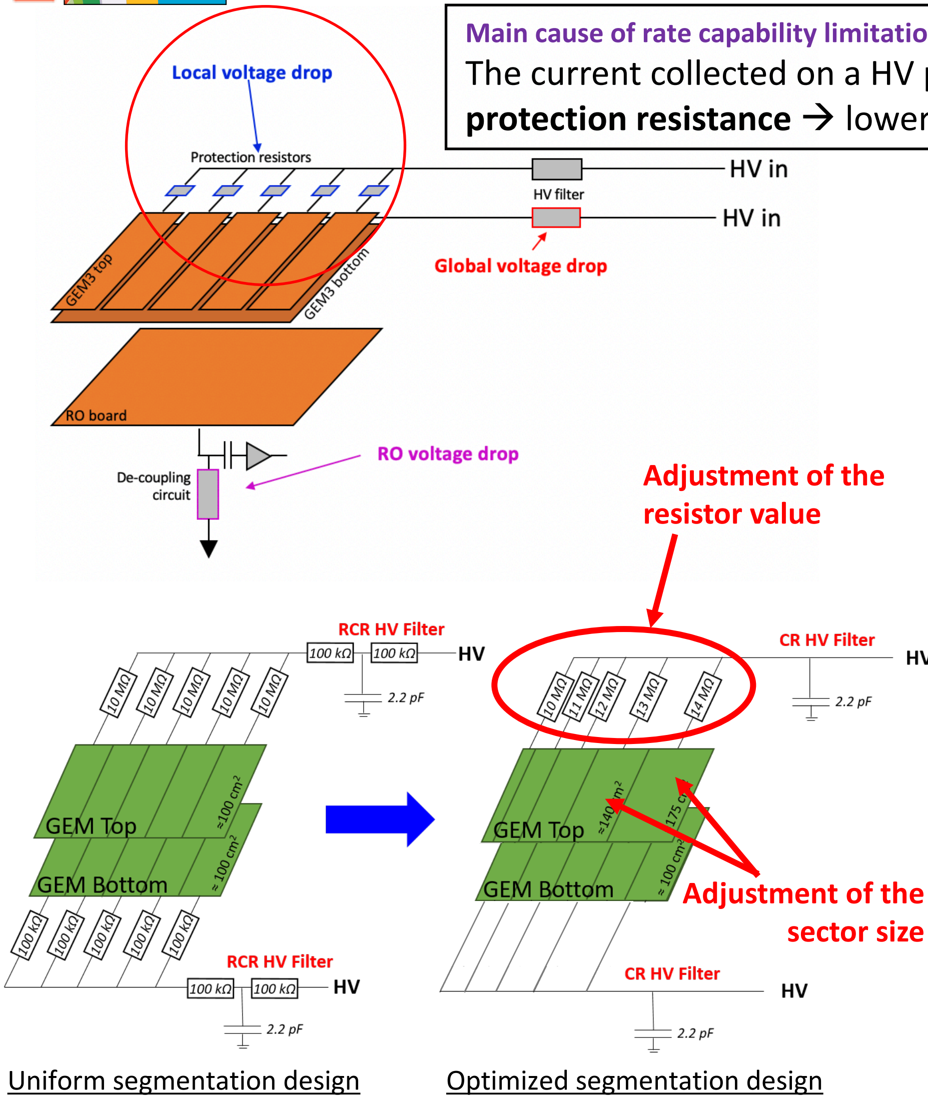
- Triple-GEM technologies can reach > MHz/cm^2
- Use of resistive circuits (HV filtering, discharge protection) can reduce the rate capability to few tens or hundreds of kHz/cm^2 or less





ME0 Rate Capability R&D

Main cause of rate capability limitation:
The current collected on a HV partition induces a voltage drop across the corresponding **protection resistance** → lower gain on this HV partition



Performance uniformity and rate capability:
- Collected current is proportional to the BKG rate
- Large gradient of rates over the ME0 trapezoid

→ Large differences in collected current for the different HV partitions

→ Voltage drops across the HV segments from 4V to 115 V

New configuration with various HV sector sizes and protection resistors on the top electrode:
- Uniform voltage drop across all HV segments of about 8V
- Uniform voltage drop = easy compensation with the power supply

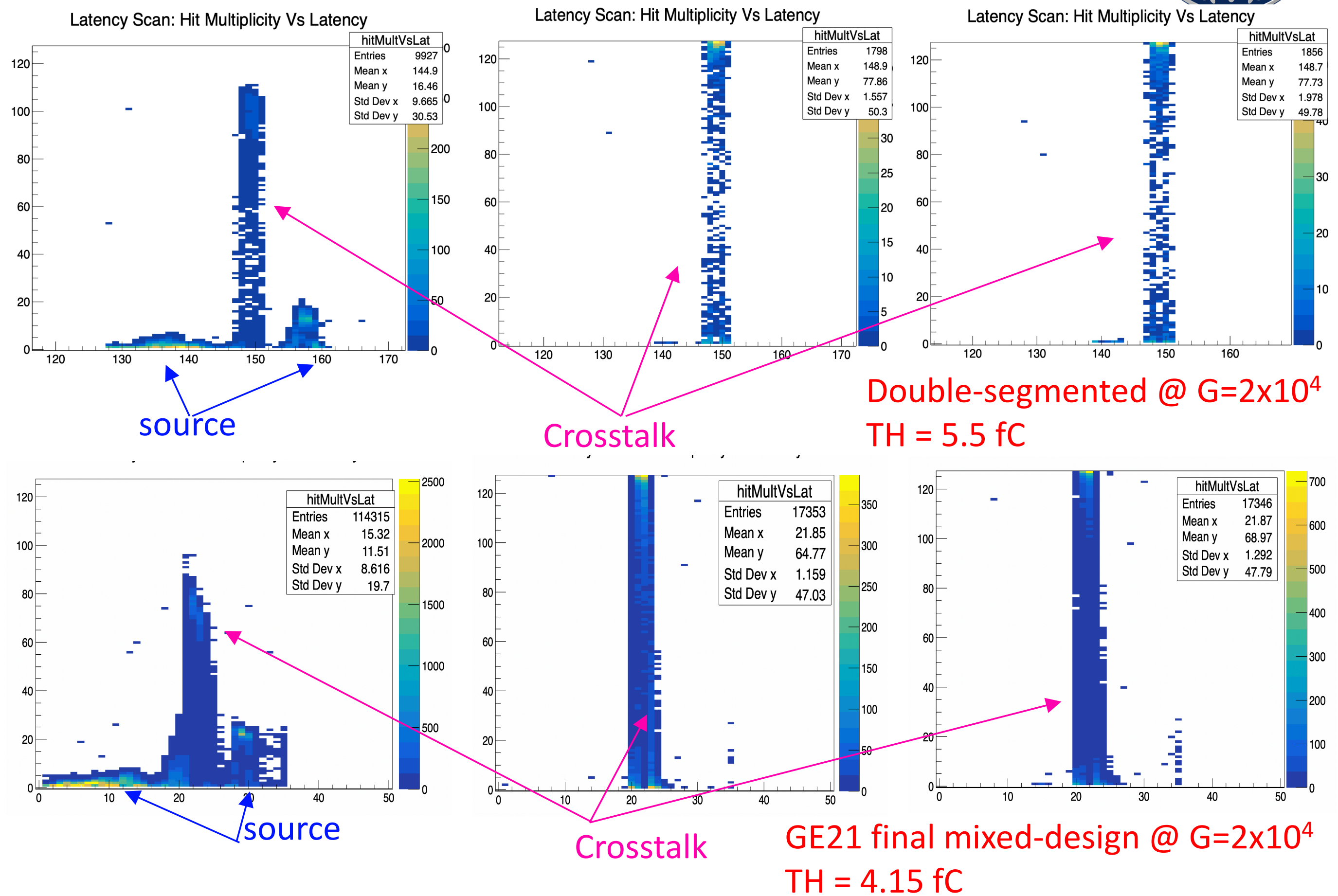
ME0 R&D work plan: See spare slides for the full schedule
- baseline validation in March 2021 (includes new HV partition design, HV filter and RO protection optimization)
- Operational optimization extended to June 2021
- Validation of the improved design in Sep. 2021

Crosstalk Studies

- Same timing characteristics for the two configuration: crosstalk signals are detected 10 BX after the initial signal

Number of channels triggered during a crosstalk event:

- Double-segmented setup: 77 strips detect crosstalk (60%) at nominal threshold
- Mixed design setup: 69 strips detect crosstalk (54%) at nominal threshold



→ Tested with an average deposited energy of 351 keV (alpha source) while the expected energy deposit in P5 is close to 288 keV

On average, only **half of the readout channels** are triggered during a crosstalk event