A Large Ion Collider Experiment

ALICE

MITIGATION OF THE PROPAGATED DISCHARGES IN GEM STACKS BY HV SCHEME OPTIMIZATION

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(TU Munich)

for the ALICE TPC Upgrade

RD51 Mini-Week

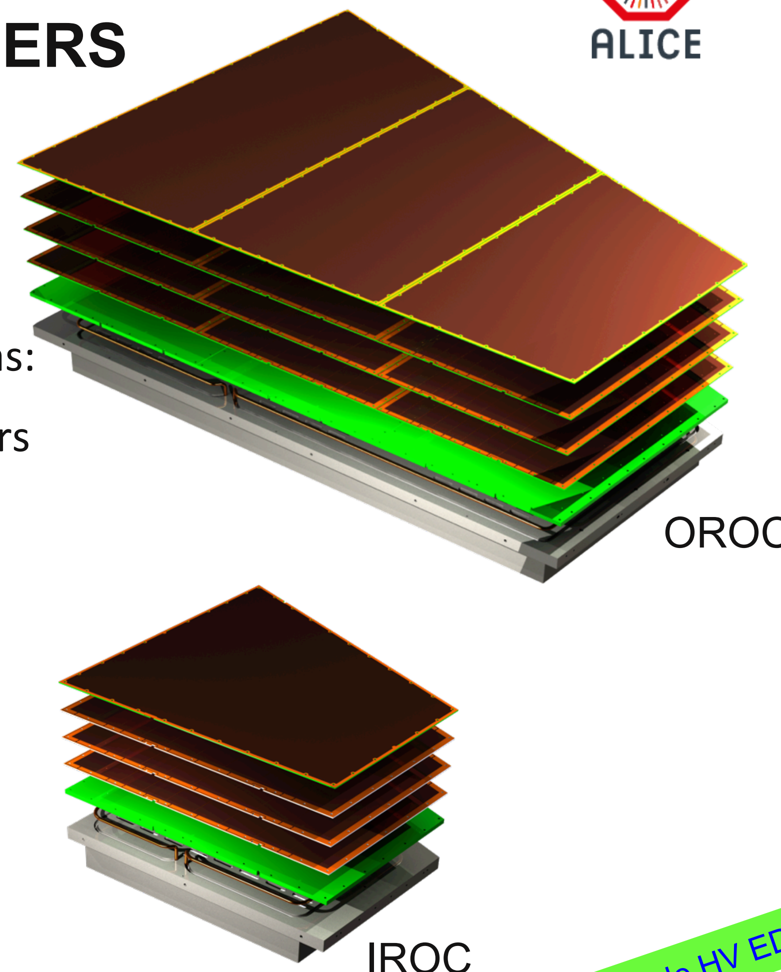
WG1, 20.02.2018

ALICE TPC UPGRADE IN NUMBERS

- Currently operated MWPC-chambers will be replaced with new, GEM-based detectors
- Mass production ongoing
  (see M. Ball's presentation later today) as well as:
- Commissioning and testing of the new chambers
- HV optimization

<u>There is a lot to protect:</u>

- **36x** IROC, **36x** OROC to be installed in LS2
- **144** quadruple stacks
- **576** GEMs
- **12000** GEM segments
- **~5×10^{9}** GEM holes
- **524160** FEE channels



The following slides are based on the ALICE TPC Upgrade HV EDR

GEM STACK

- All GEMs segmented on the top side; bottom side not segmented
- Reduce energy of discharges in GEMs
- All segments on a foil connected in parallel via R_L at each segment
- R_L = 5 MΩ

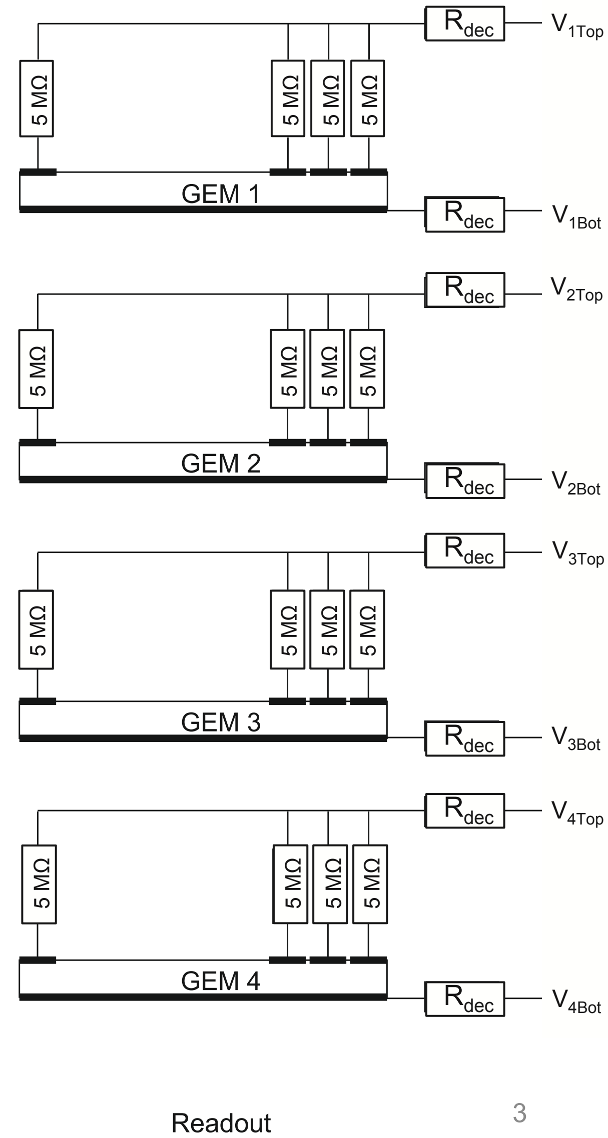
IROC
- 18 HV segments
- <A> = 92.5 cm^2

OROC1
- 20 HV segments
- <A> = 86.9 cm^2

OROC2
- 22 HV segments
- <A> = 104.5 cm^2

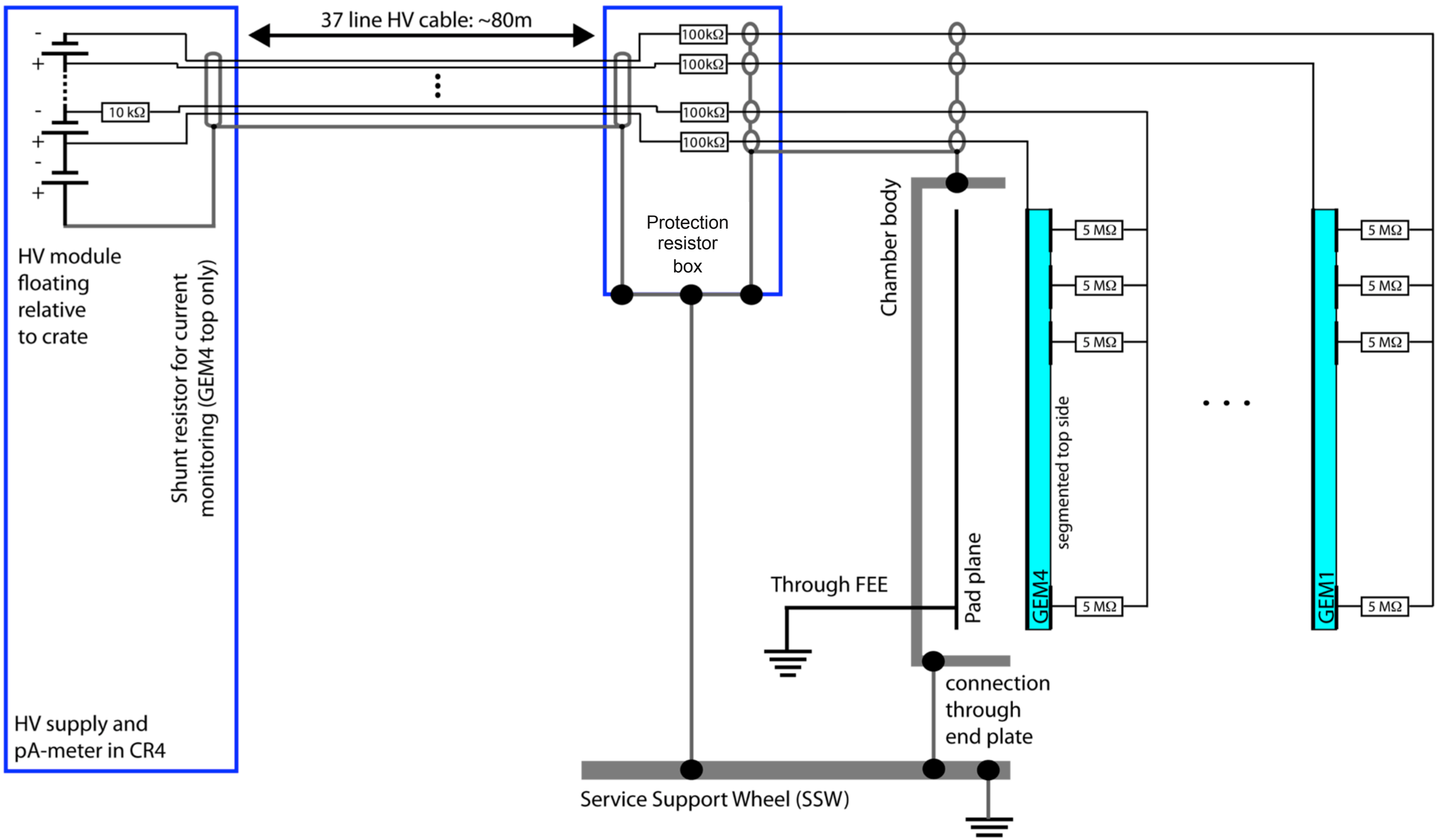
OROC3
- 24 HV segments
- <A> = 122.1 cm^2

Settings	E_{T1} [kV/cm]	E_{T2} [kV/cm]	E_{T3} [kV/cm]	E_{IND} [kV/cm]	ΔV_{G1} [V]	ΔV_{G2} [V]	ΔV_{G3} [V]	ΔV_{G4} [V]	V_{G1T} [V]	IBF (%)	σ (%)
A	4.0	4.0	0.1	4.0	270	230	288	359	3567	0.65	12.7
B	3.5	3.5	0.1	3.5	270	230	320	320	3260	1.12	10.8



UPGRADED ALICE TPC

HV scheme

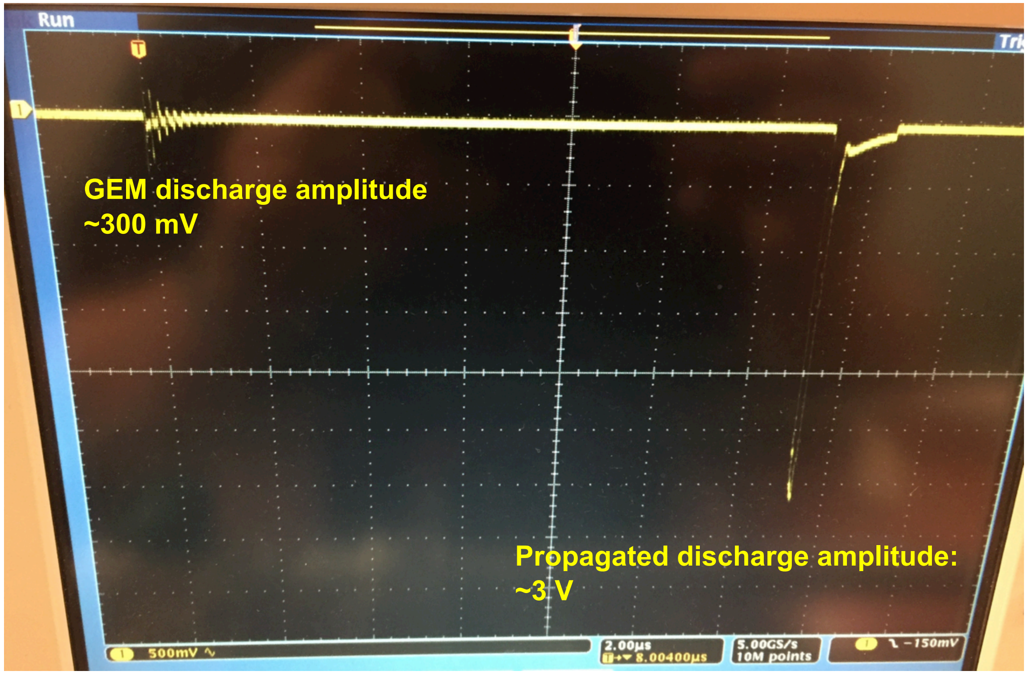


DISCHARGE PROPAGATION

DISCHARGE PROPAGATION

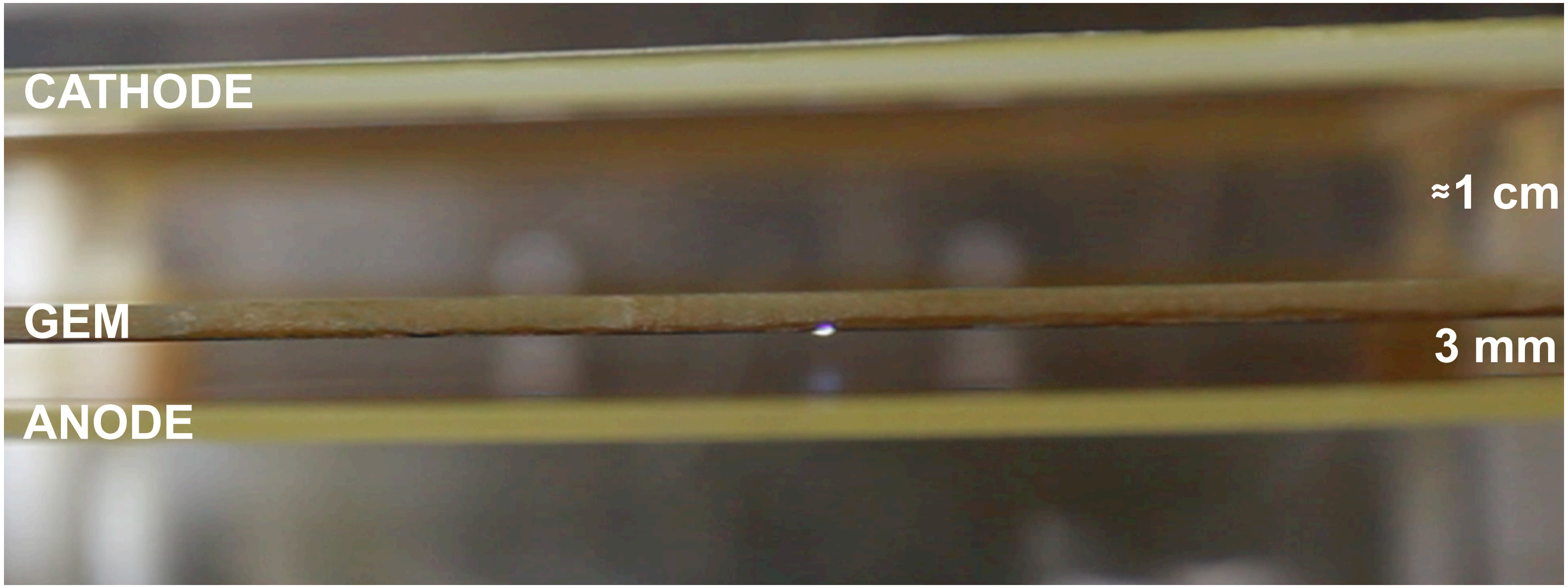
- **Propagated/secondary discharge:**

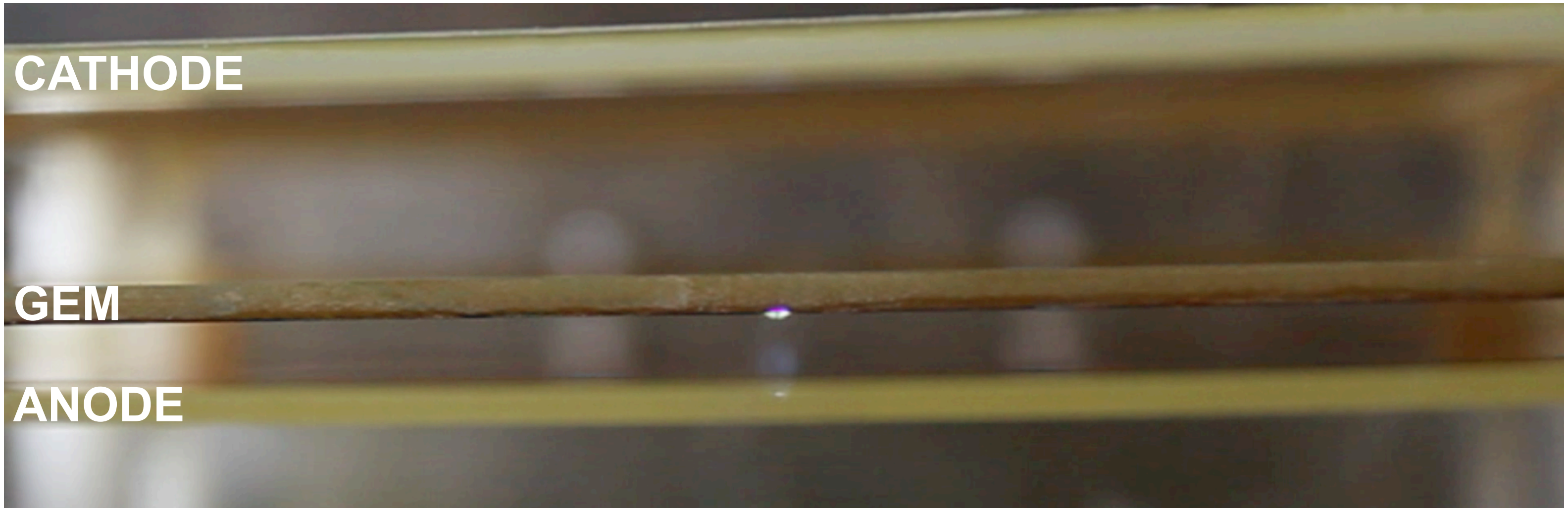
  discharge in transfer or induction gaps triggered by a primary spark in GEM
- Amplitude of such a discharge about a factor 10 larger than primary one.
- Large signal can be associated with the development of a spark between GEM and GEM/padplane



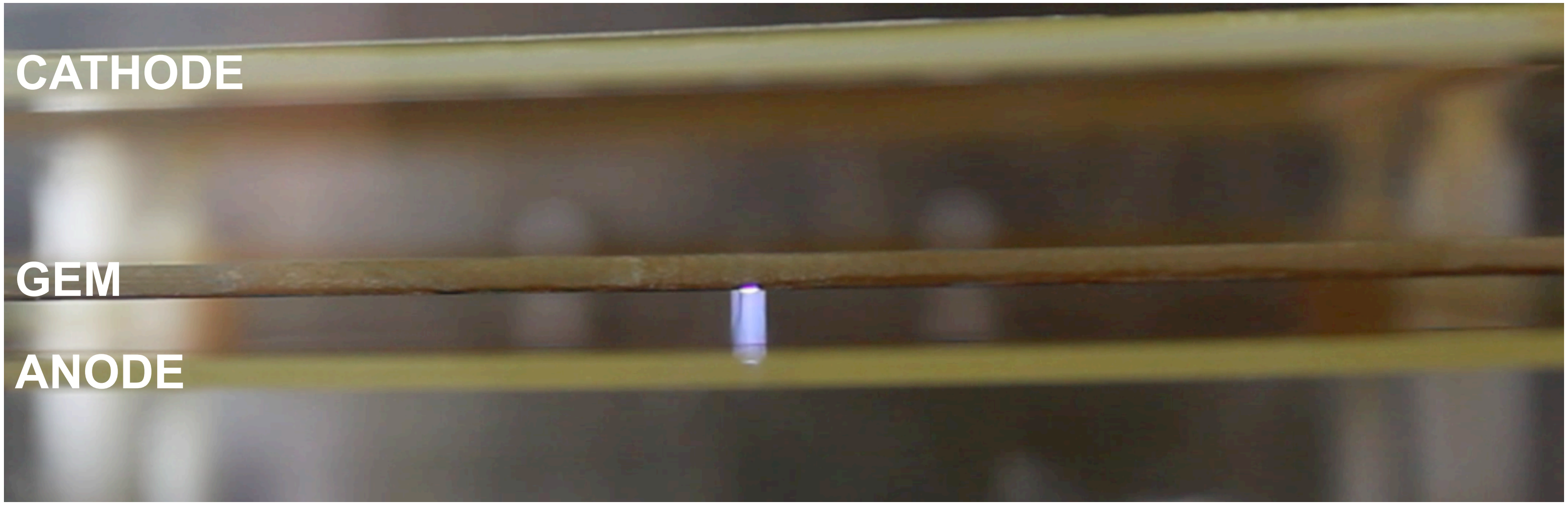
- **May be violent: risk of irreversible damage to the detector**

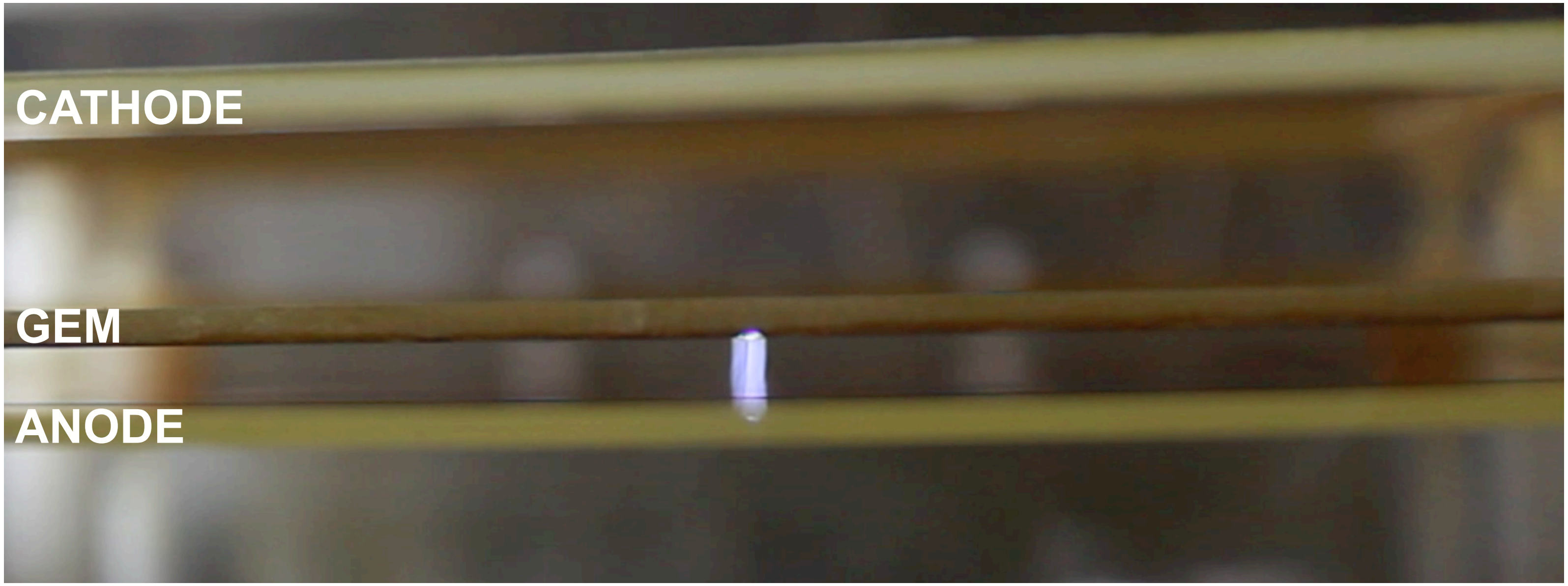
DISCHARGE IN A SINGLE GEM HOLE





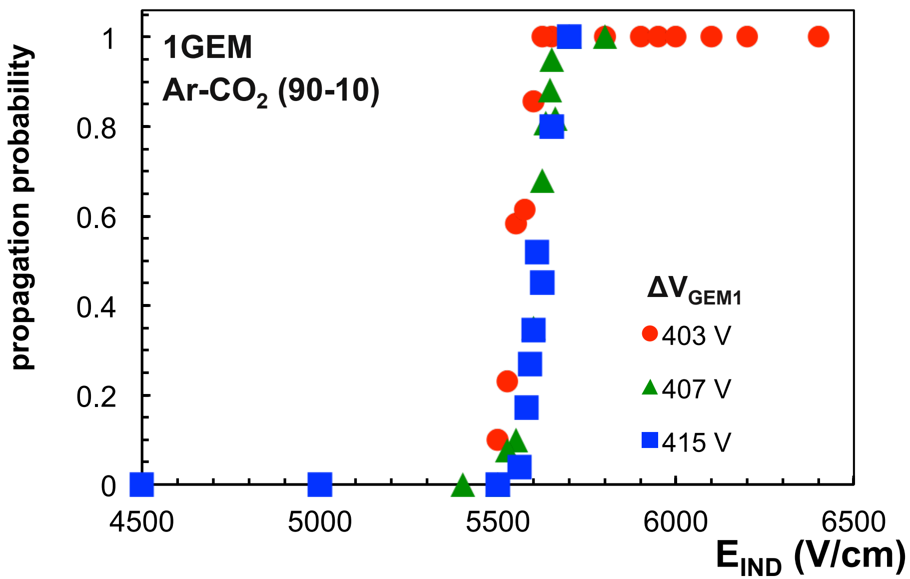
SECONDARY DISCHARGE IN THE INDUCTION GAP

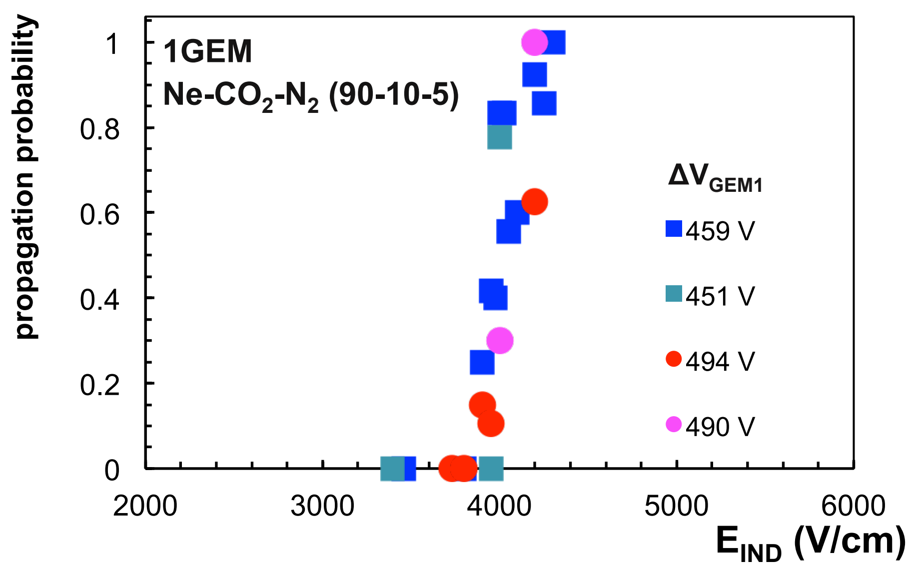




FACTS

- Observed at relatively low fields, much below amplification field:
  - $E_{\alpha>0}$ ~ 5 kV/cm (Ne-CO_2-N_2)
  - $E_{\alpha>0}$ ~ 9 kV/cm (Ar-CO_2)
- Field increase in the gap?
  - Not confirmed by measurements with HV probes
  - Foil bending excluded
  - Propagation probability drops with increasing value of the resistor in series on the bottom side of GEM (!) (more recent results in backup)
- Relatively long time intervals between primary and propagated discharge (up to 50 us)
  - Ion related?
  - Shorter times measured in Ne-based mixtures (mobility)
  - Measurements continue (CERN, TUM) Fruitful discussions with the GDD group.





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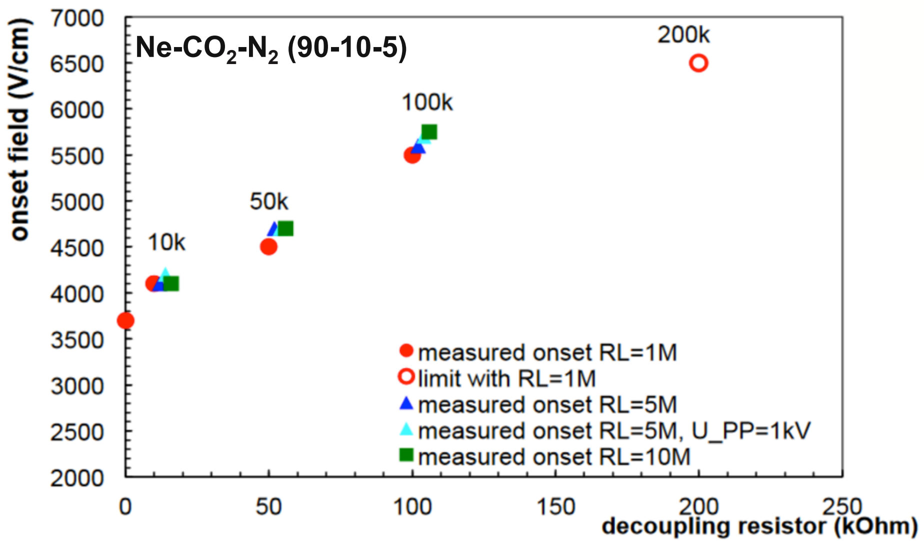

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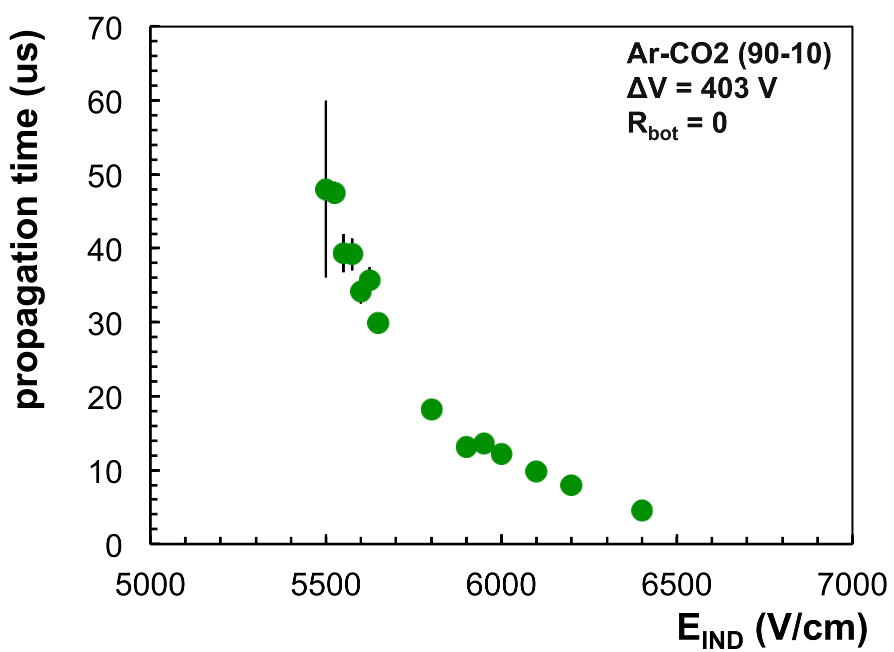
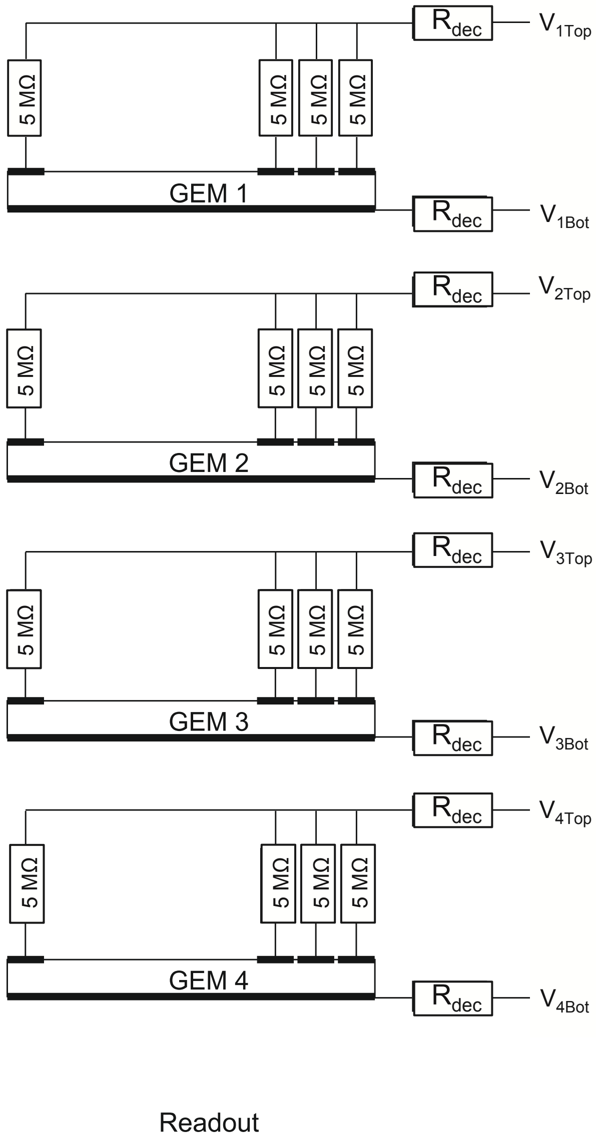
    - Measurements continue (CERN, TUM) Fruitful discussions with the GDD group.
    - Hope to solve the puzzle soon!



HV SCHEME OPTIMIZATION

RC IN THE SYSTEM



- PS impedance
- 10 kΩ shunt in current meter connected to GEM4TOP channel
- ~10 nF capacitance of a ~80 m HV cable
- Decoupling resistor (1 per HV cable, top and bottom side)
  - Decouple HV supply line form a GEM electrode
  - Current choice: 100 kΩ; acceptable potential drop
- ~100 pF capacitance of a ~1 m HV cable
- Loading resistors (top side of the foil)
  - Quench a spark, reduce current, protect GEM segment
  - Reduce current flowing from the PS in case of a short (allow for *n* shorts in a foil)
  - Voltage (thus gain) drop due to the (ion/electron) current
  - Final choice: 5 MΩ (for GEM1,2,3,4)

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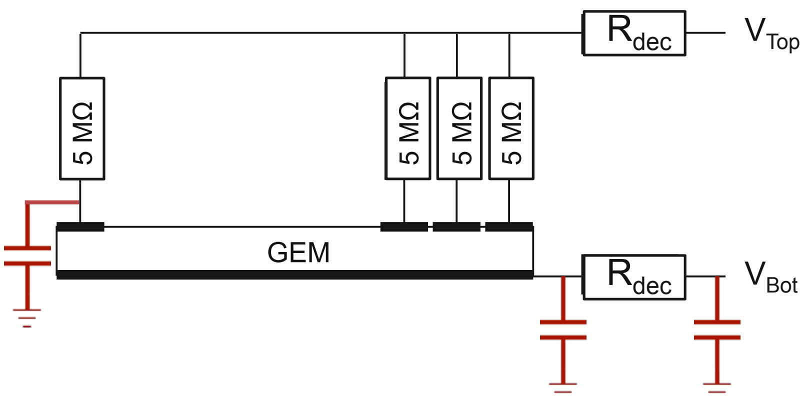

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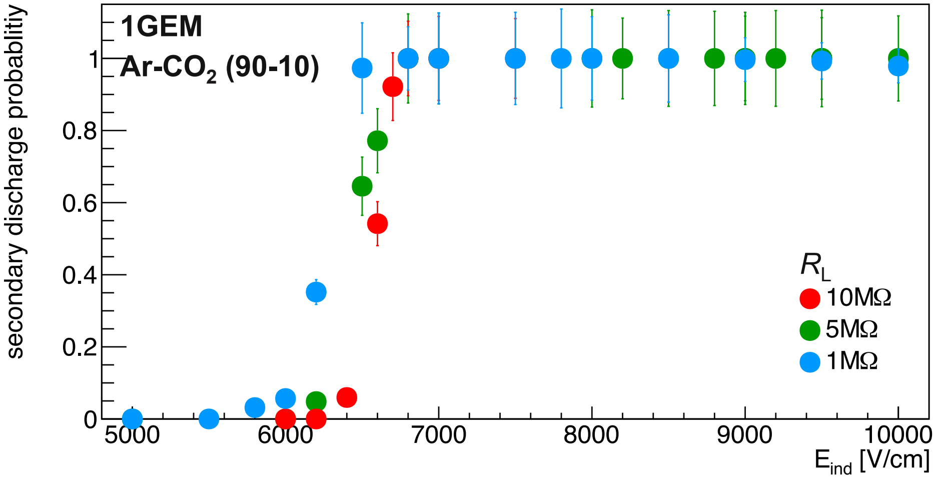
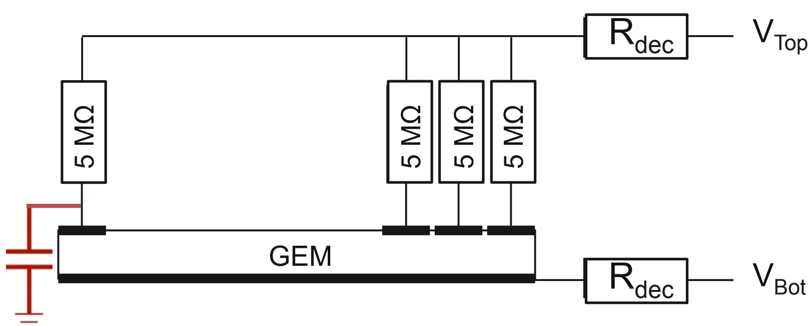
PARASITIC RC MEASUREMENTS IN Ar-CO_2 (90-10)



- Propagation probability does not depend on the loading resistor value
- Nominal value R_L = 5 M



- Extra capacitance (e.g. cable) between the top loading resistor and the top GEM electrode may influence the propagation behavior

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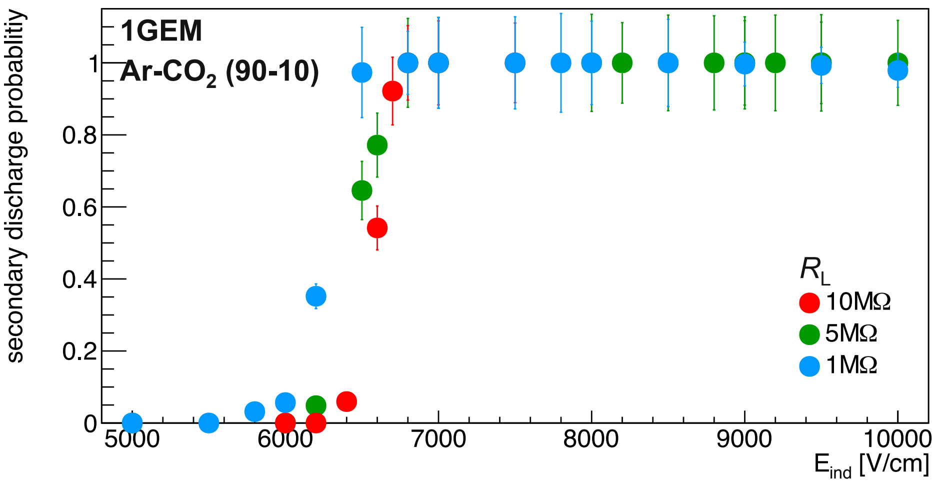

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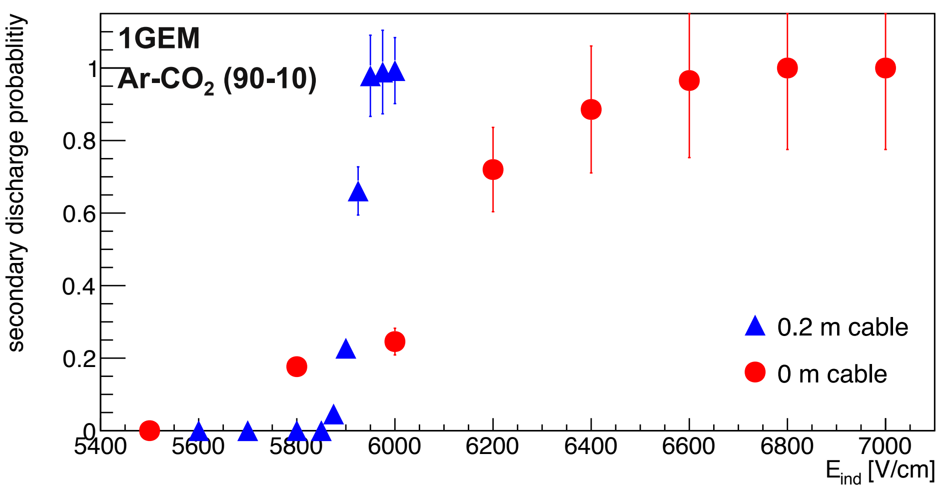

- Extra capacitance (e.g. cable) between the top loading resistor and the top GEM electrode may influence the propagation behavior
- Effect of an extra energy reservoir, causes substantial increase of GEM_{Bot} voltage
- ✓ Loading resistors soldered directly at the GEM foil

PARASITIC RC MEASUREMENTS IN Ar-CO_2 (90-10)

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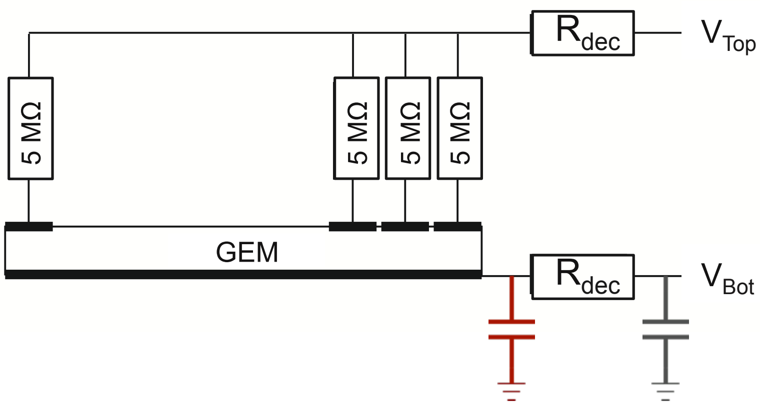
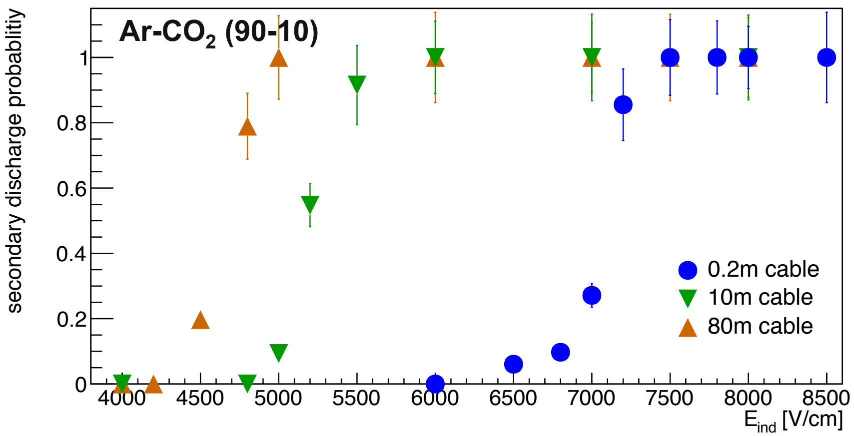
- Cable between bottom decoupling resistor and GEM

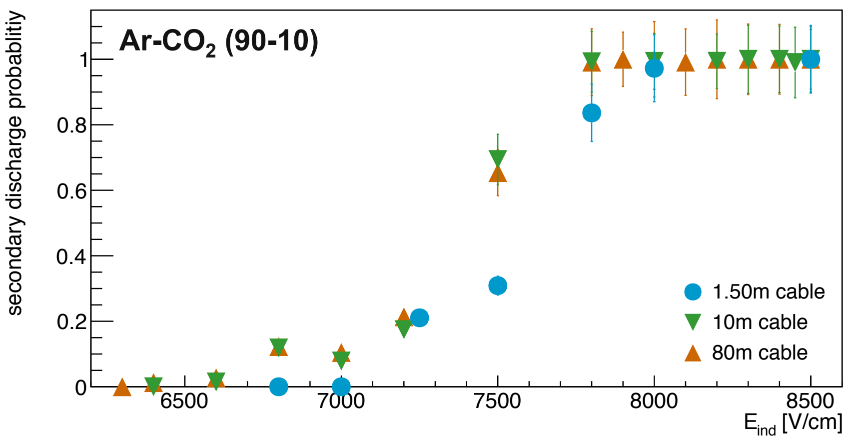


- Cable between a Power Supply and bottom decoupling resistor

PARASITIC RC MEASUREMENTS IN Ar-CO_2 (90-10)



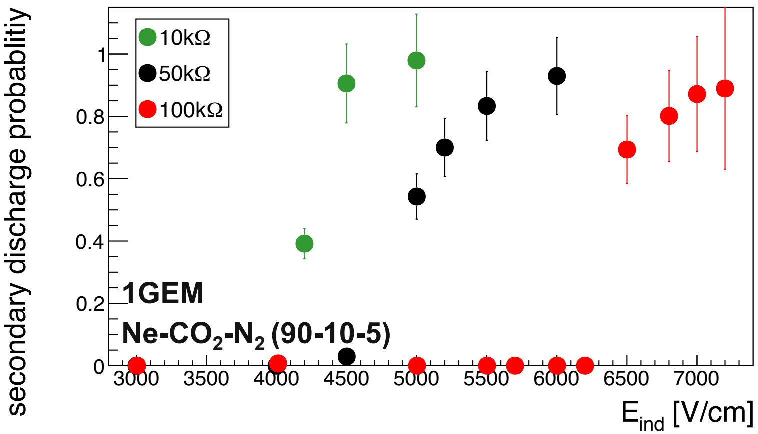
- **Cable between bottom decoupling resistor and GEM**
- R_L = 5 MΩ, $R_{dec,bot}$ = 200 kΩ
- Propagation probability increases with the parasitic capacitance (cable length) introduced between R_{bot} and GEM
- Effect of the stored energy
- Necessary to install decoupling resistors close to the chambers



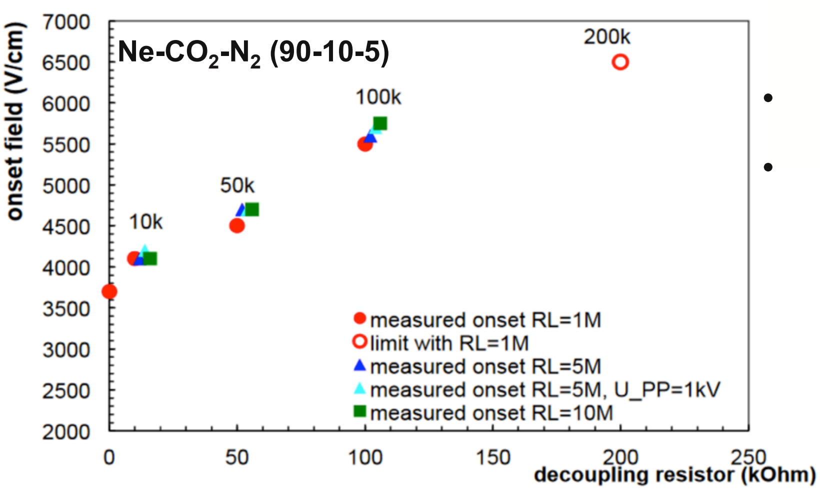
- **Cable between a Power Supply and bottom decoupling resistor**
- Effect of the decoupling resistor ($R_{dec,bot}$ = 200 kΩ, R_L = 5 MΩ)
- Cable length (between the PS and $R_{dec,bot}$) does not influence the propagation probability

✓ Decoupling resistor decouples long cables well

MEASUREMENTS IN Ne-CO_2-N_2 (Ne-CO_2-N_2)

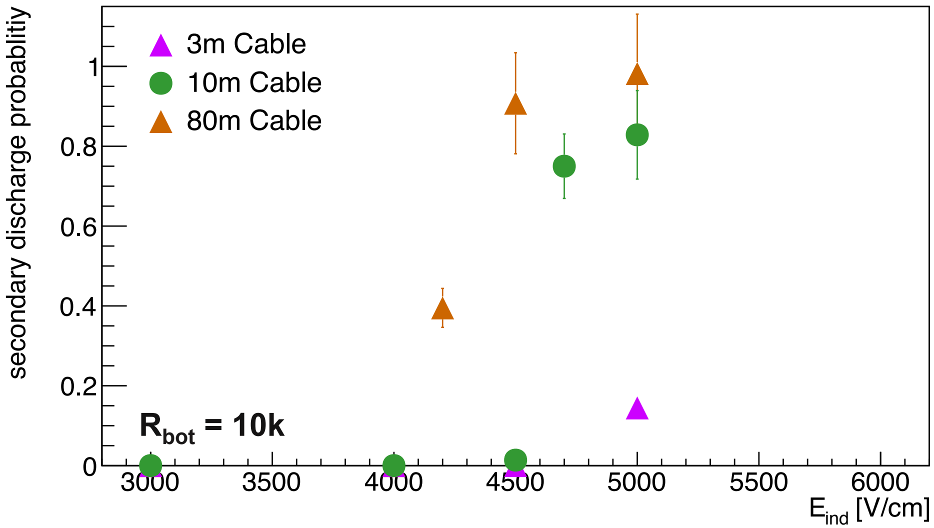


- Propagation curves measured in the nominal mixture
- 80 m cable form the PS to simulate realistic conditions
- 1.5 m between $R_{dec,bot}$ and GEM_{bot}
- Clear dependence on $R_{dec,bot}$ value

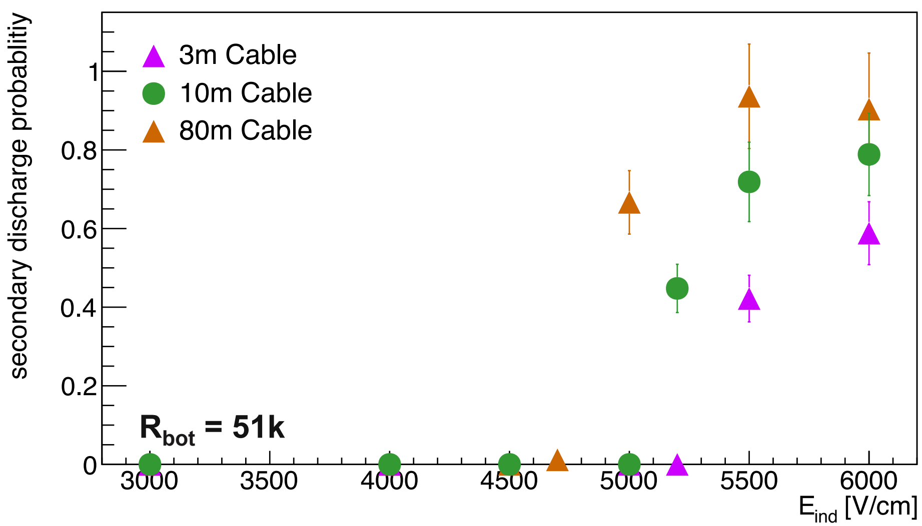


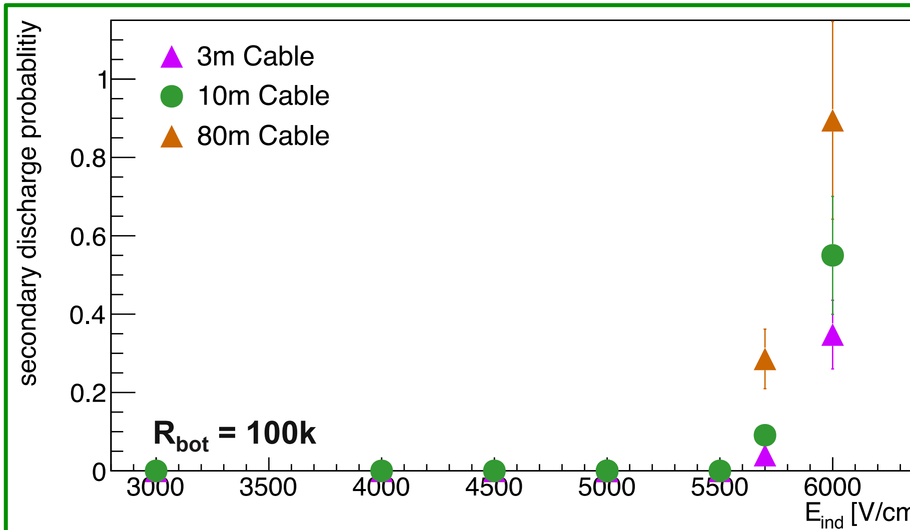
- Onset field measurement with a CPS
- 80 m cables between the CPS and resistors

PARASITIC RC MEASUREMENTS IN $Ne\text{-}CO_2\text{-}N_2$



- “Decoupling power” of 10 kΩ resistor rather poor, visible dependence on the cable length
- Situation improves with larger $R_{dec,bot}$
- With $R_{dec,bot}$ > 100 kΩ marginal dependency on the cable length
- Higher resistance clearly preferable





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MITIGATION OF PROPAGATED DISCHARGES

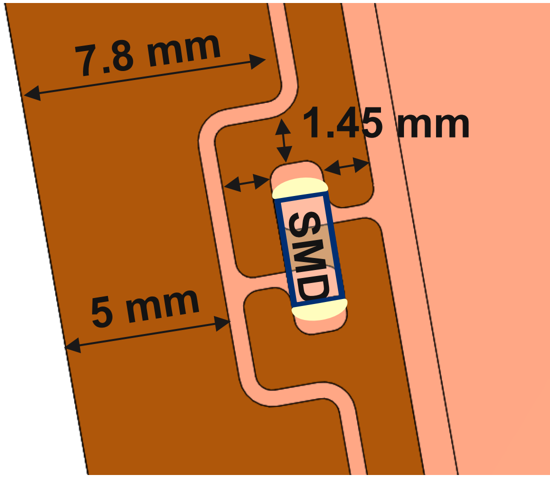
Summary

- Choose higher value of the decoupling resistance: $R_{dec,\mathrm{bot}}$ = 100 kΩ
- Value of the resistor can be adjusted until final installation but also during the TPC operation
- HV settings with lower fields preferable (e.g. B-settings, $E_{\mathrm{T1,2,IND}}$ = 3.5 kV/cm)
- Minimize cable length between the $R_{\mathrm{dec,bot}}$ and GEM (~2 m)

TOP DECOUPLING RESISTOR VALUE – $R_{dec,top}$

For completeness…

- We keep value of the top decoupling resistor same as for the bottom side: $R_{dec,top}$ = 100 kΩ
- $R_{dec,top}$ > 0 needed to decouple HV power supply and 80 m cable from a GEM top electrode
  - Otherwise PS connected directly 1.45 mm away from the active GEM area
- $R_{dec,top}$ < 1 M
  - Larger GEM4T and ET3 voltages variations with load oscillations
  - Damping of the current oscillation amplitude in GEM4T current monitor



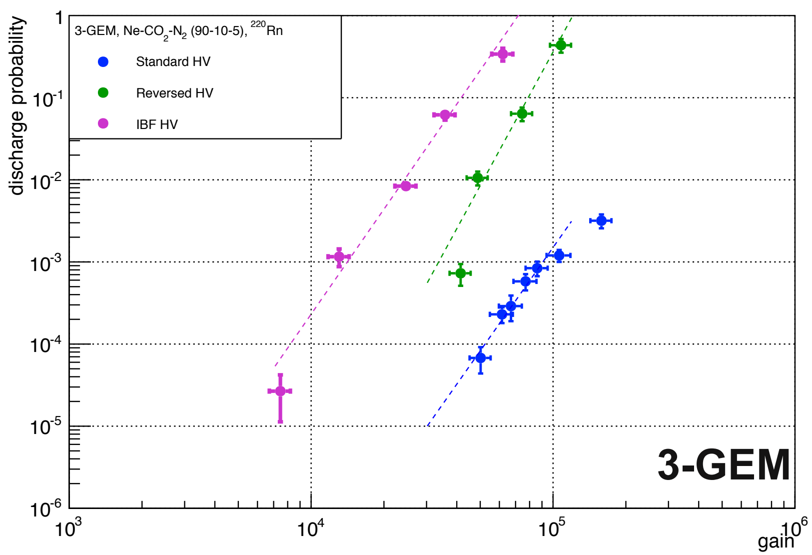
BACKUP

1. Primary discharge probability with 4-GEM readout chambers
2. Cascaded power supply response to a discharge

DISCHARGE PROBABILITY

DISCHARGE PROBABILITY

Influence of HV settings



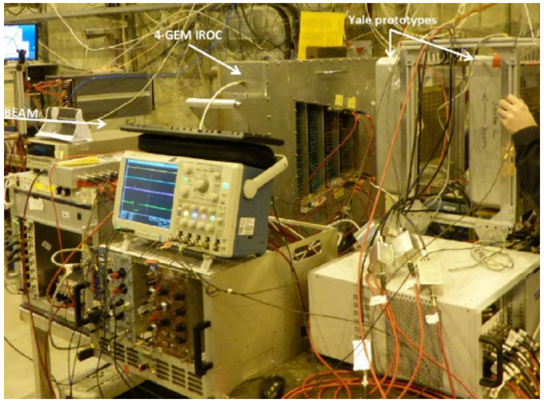
- Different HV settings have been tested with a 3-GEM configuration
- "Standard" → "IBF"
  - Standard – optimized for stability (COMPASS)
  - IBF → optimized for IBF
- Significant drop of stability while using IBF settings with a typical 3-GEM configuration

- **4-GEM configuration,** optimized for energy resolution and IBF is also stable against electrical discharges
- Measurements for HV settings similar to **A**

	S-S-S 'standard' HV G = 2000	S-S-S-S *IB* = 2.0% G = 2000	*IB* = 0.34% G = 1600	S-LP-LP-S *IB* = 0.34% G = 3000	*IB* = 0.34% G = 5000	*IB* = 0.63% G = 2000
^{220}Rn $E_\alpha = 6.4$ MeV rate = 0.2 Hz	$\sim 10^{-10}$			$< 2\times10^{-6}$	$< 7.6\times10^{-7}$	
^{241}Am $E_\alpha = 5.5$ MeV rate = 11 kHz						$< 1.5\times10^{-10}$
^{239}Pu+^{241}Am+^{244}Cm $E_\alpha = 5.2+5.5+5.8$ MeV rate = 600 Hz		$< 2.7\times10^{-9}$	$< 2.3\times10^{-9}$	$(3.1\pm0.8)\times10^{-8}$		$< 3.1\times10^{-9}$
^{90}Sr $E_\beta < 2.3$ MeV rate = 60 kHz					$< 3\times10^{-12}$	

DISCHARGE PROBABILITY

SPS, December 2014 (RD51 test beam)



- **150 GeV/*c* pion beam hitting Fe absorber**
  - ~5×10^{11} particles accumulated
  - Comparable to the number of particles expected in the TPC during a typical yearly Pb-Pb run at a collision rate of 50 kHz (per GEM stack)

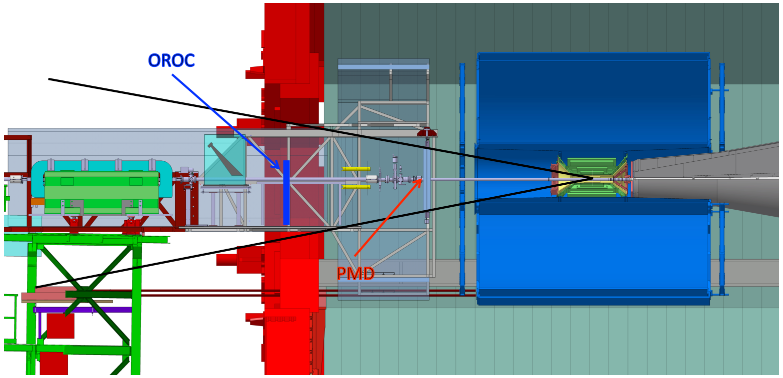
- HV settings comparable to “Settings B”, gain = 2000

- **Discharge probability**: $(6 \pm 4)\times10^{-12}$ per incoming hadron

- **Estimate for Run 3:**
  - 650 discharges in the TPC per typical yearly Pb-Pb run
  - 5 per stack

DISCHARGE PROBABILITY

LHC, operation at P2



- Test IROCs and OROCs under radiation conditions that are comparable to Run 3
- IROC and OROC are placed in the miniframe, close to the beam pipe
- In 150 kHz pp, **direct** load on ROCs in this position is comparable to that on ROCs installed in the TPC in Run 3
- More on the ROC and CPS tests at P2 → see talk by Robert Münzer

	Running time	Current spikes (> 500 nA)	Spikes per Pb-Pb year (~200h) per stack
Settings A (100%) Gain ~2500	33h 17' 55''	30	180
Settings B (100%) Gain ~2000	504h 46' 08''	7	3
Settings B (102%) Gain ~4000	25h 37' 19''	7	55

- Settings with lower ΔV_{GEM4} and $\Delta V_{GEM3}/\Delta V_{GEM4}$ = 1.0 preferable (settings B)

CASCADED PS RESPONSE ON A DISCHARGE

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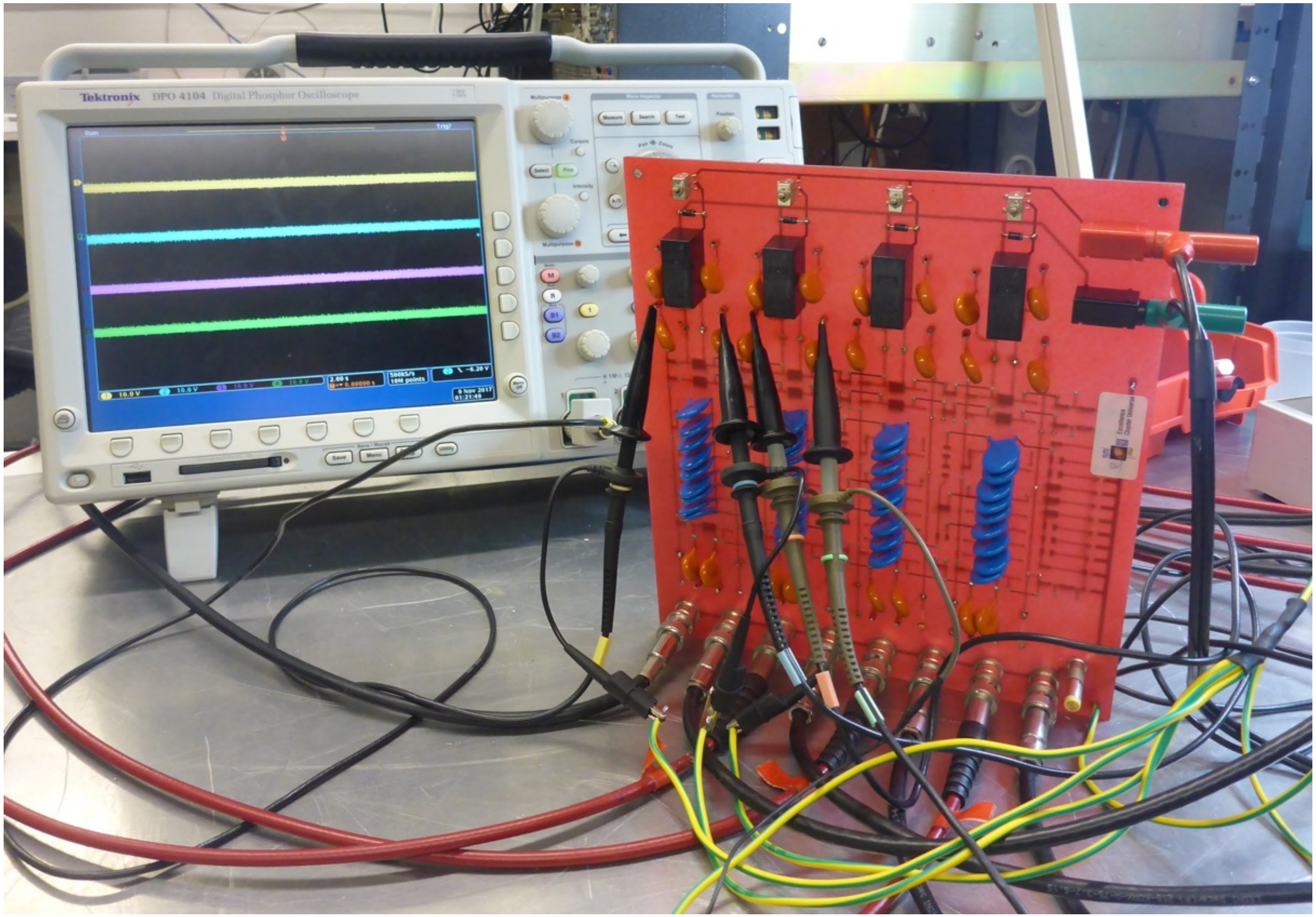
PCB GEM SIMULATOR

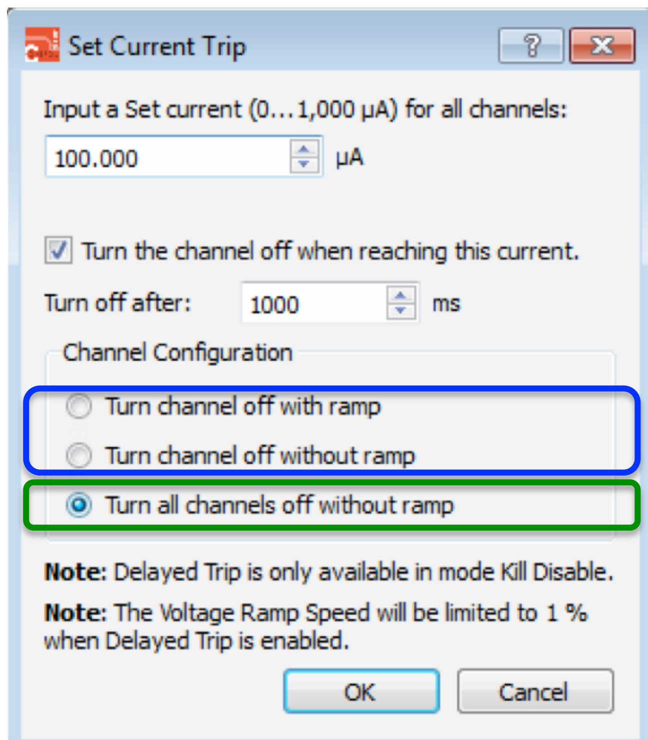


- 4GEM
- IROC equivalent
- R_L = 5 MΩ
- R_{dec} = 100 kΩ
- Test Probes:
  10:1, 100:1, 1000:1
- Readout via
  2.2 nF decoupling C or
  directly at the HV line
  (1000:1 probe)
- Discharge/short:
  relay – trip behavior
  GDT – discharge behav.

CASCADED PS TESTS

ISEG prototype

- Check different tripping modes
  - Don’t turn the channel off
    (voltage drops to maintain the current limit)
  - Single channel trip after overcurrent detected
  - With or w/o ramp-down, delay, etc.
  - All channels turn off without ramp after overcurrent detected (ISEG feature)



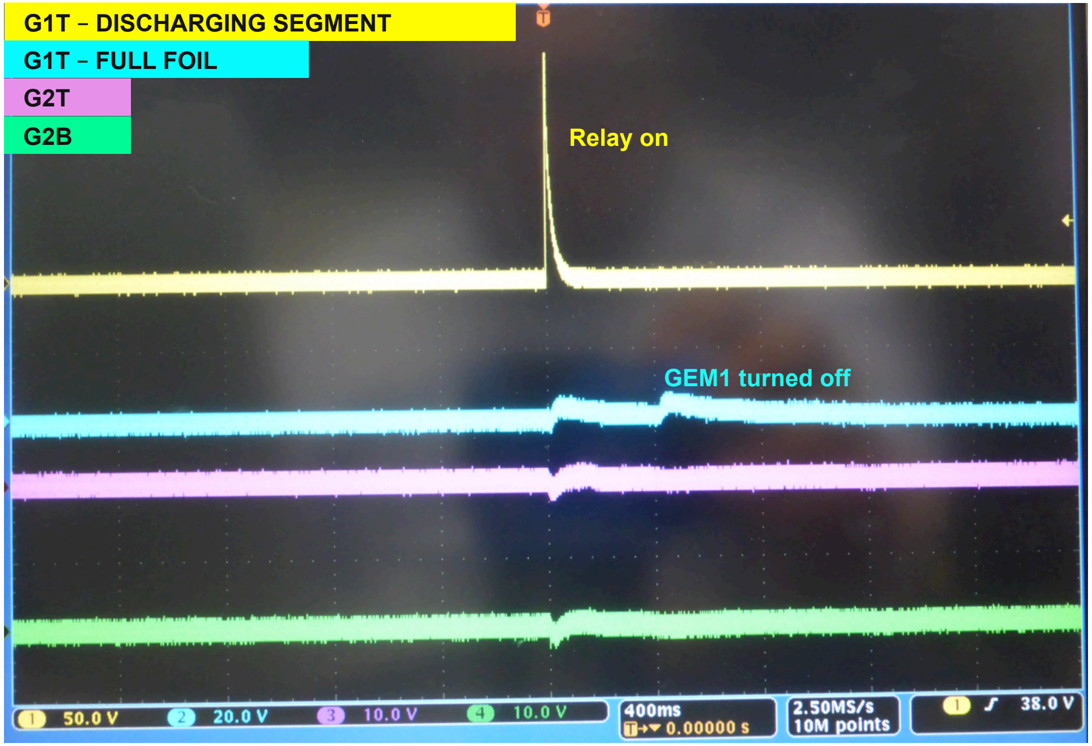
Single channel reaction

All channels reaction

CASCADED PS TESTS

Single channel reaction settings

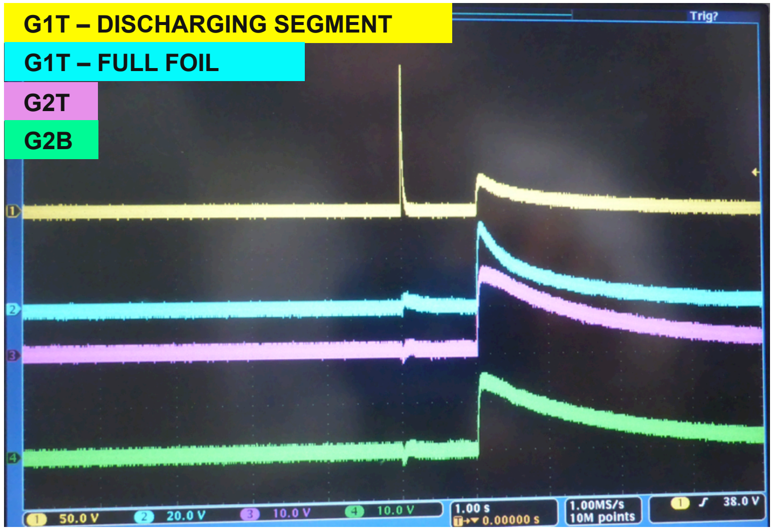
- Possible small overvoltage $\mathcal{O}$(V) in a discharge moment (for other-than-discharging GEM)
- No reaction of other channels (unless due to capacitive coupling, few volts)
- All CPS reactions on >1 ms scale,
  (longer than the discharge/propagation time-scale)
- All reactions safe for GEMs

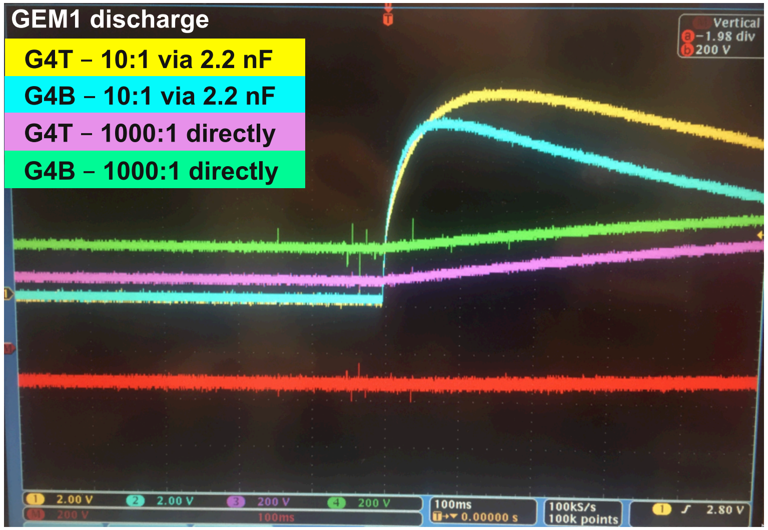


CASCADED PS TESTS

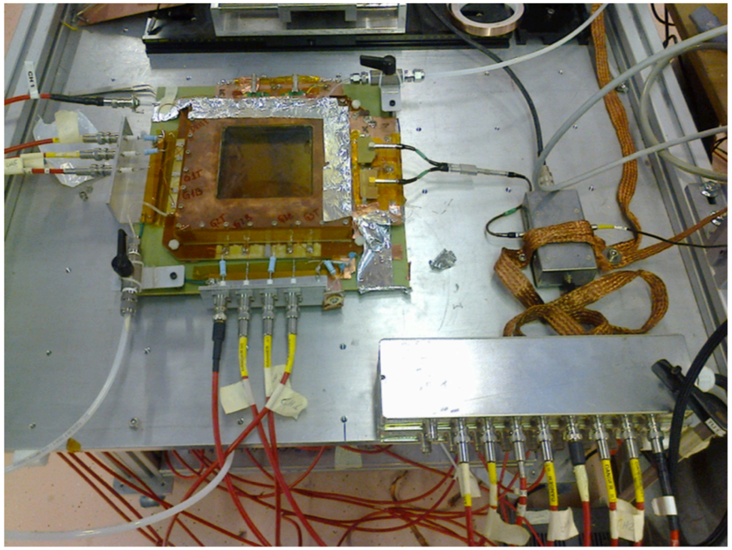
All channels turned off without ramp (ISEG feature)

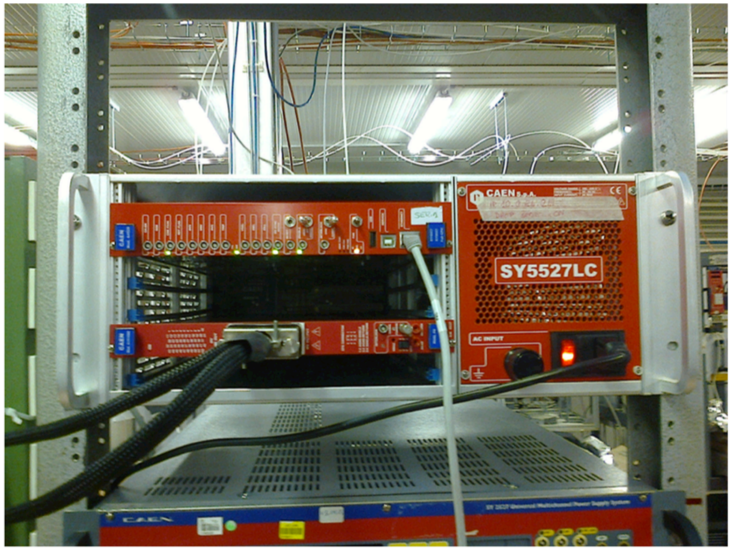
- All electrodes discharge to ground with a long time constant (RC ~2s, no direct connection to GND)
- All channels trip together within 1 ms
- Overvoltage during a trip excluded or marginal
- No dependency of the PS reaction on the I_{limit} found





TESTING CAEN CPS





- CAEN Cascade power supply: second release, current resolution 100 pA
- Crate SY5527LC + GECO program to control and monitor the PS

- Triple GEM stack, 10x10cm2 (from RD51), 70%Ar + 30%CO2
- Resistor 470 kΩ on the top and 10 kΩ on the bottom of each GEM (time before final choice was made)

- Reaction on an overcurrent: ramp channel(s) down. No overvoltage measured.
- No possibility to turn all channels off without ramp

SUMMARY II

- Discharge probability for the nominal S-LP-LP-S solution compatible with the well-established, safe settings for the 3-GEM trackers
- Safe HV scheme identified to minimize the effects of a spark in a GEM and mitigate the risk of a discharge propagation:
    - Top side of a GEM foil segmented
    - R_L = 5 MΩ soldered directly at the GEM segment
    - Decoupling resistors $R_{dec,bot} = R_{dec,top}$ = 100 kΩ
    - Decoupling resistors need to be installed close to the chambers
- CPS reaction on a discharge event safe for the foils in a GEM stack

BACKUP SLIDES

IROC SEGMENTATION

18 HV segments on one side

(opposite side not segmented)

- Reduce energy of discharges
- Connected in parallel via R_L at each segment

Average area: 92.5 cm²

Follows the padplane layout

Pad size: 7.5 x 4 mm²

Segment boundaries overlap with pad-row boundaries

6 pad rows	96.4 cm²
6 pad rows	92.4 cm²
6 pad rows	88.8 cm²
6 pad rows	85.3 cm²
7 pad rows	95.2 cm²
7 pad rows	90.3 cm²
8 pad rows	97.4 cm²
8 pad rows	91.1 cm²
9 pad rows	95.3 cm²

OROC SEGMENTATION

- **OROC3**
  24 segments
  <A> = 122.1 cm^2
  Pad: 15 x 6 mm^2

- **OROC2**
  22 segments
  <A> = 104.5 cm^2
  Pad: = 12 x 6 mm^2

- **OROC1**
  20 segments
  <A> = 86.9 cm^2
  Pad: = 10 x 6 mm^2

- Opposite sides not segmented
- Segmentation follows the padplane layout.

2 pad rows	138.9 cm^2
2 pad rows	123.6 cm^2
2 pad rows	122.0 cm^2
2 pad rows	120.5 cm^2
2 pad rows	118.9 cm^2
2 pad rows	117.3 cm^2
2 pad rows	115.7 cm^2
2 pad rows	114.1 cm^2
2 pad rows	112.6 cm^2
2 pad rows	111.0 cm^2
2 pad rows	109.4 cm^2
3 pad rows	161.9 cm^2

2 pad rows	83.8 cm^2
2 pad rows	82.5 cm^2
2 pad rows	81.5 cm^2
3 pad rows	120.7 cm^2
3 pad rows	118.4 cm^2
3 pad rows	116.1 cm^2
3 pad rows	113.8 cm^2
3 pad rows	111.6 cm^2
3 pad rows	109.3 cm^2
3 pad rows	107.0 cm^2
3 pad rows	105.0 cm^2

3 pad rows	84.6 cm^2
3 pad rows	82.8 cm^2
3 pad rows	81.2 cm^2
3 pad rows	79.2 cm^2
3 pad rows	78.0 cm^2
3 pad rows	76.5 cm^2
4 pad rows	99.7 cm^2
4 pad rows	96.9 cm^2
4 pad rows	94.1 cm^2
4 pad rows	96.0 cm^2

PS TEST WITH THE GEM-PCB SIMULATOR

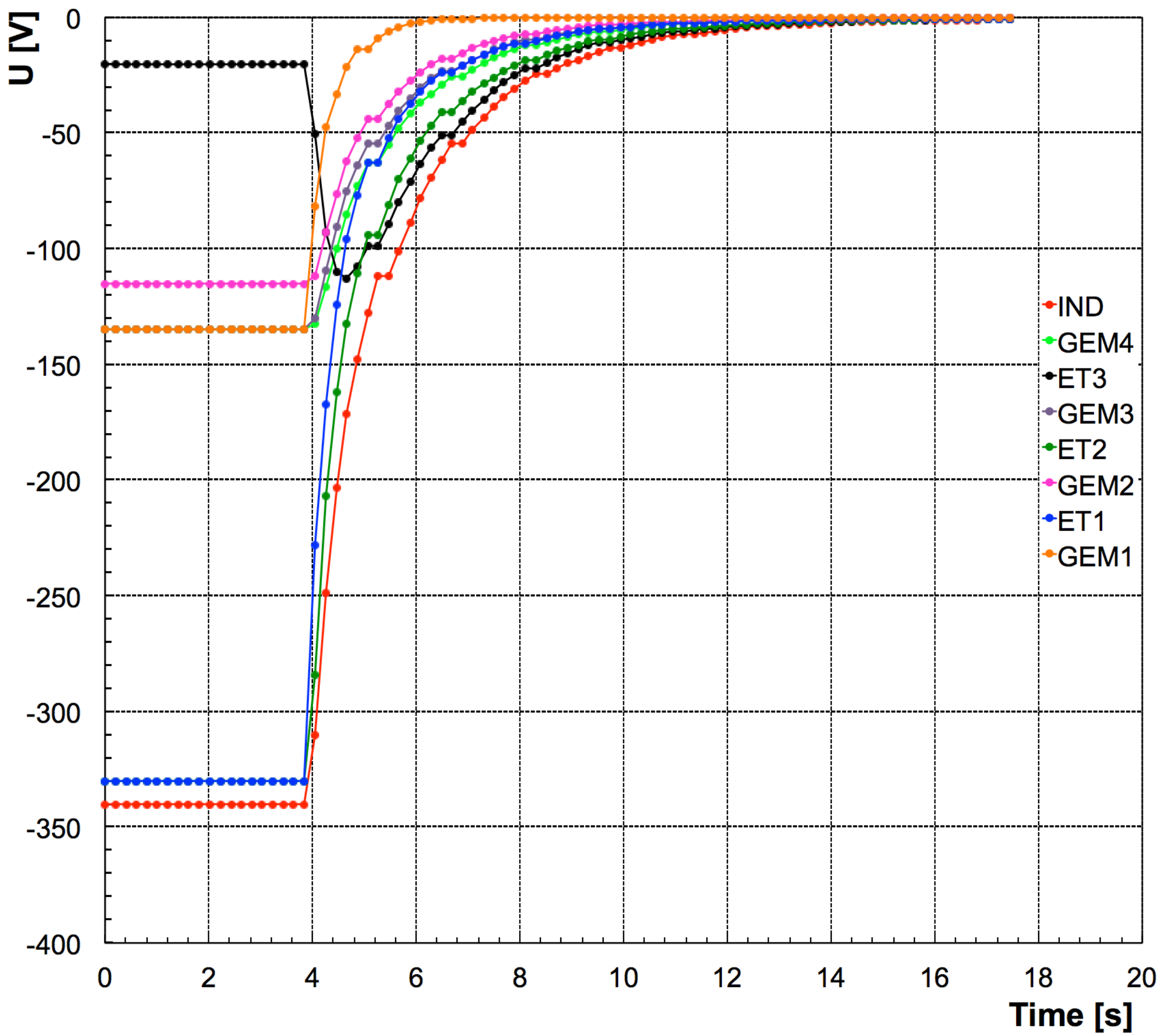
ALICE

TRIP CHARACTERISTICS

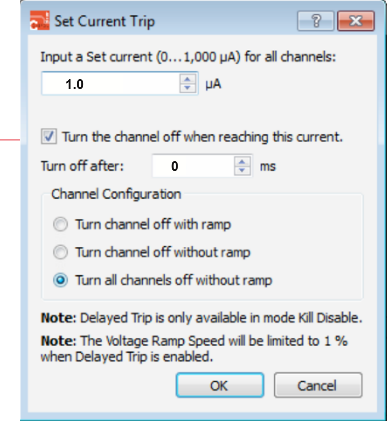
ISEG EHS 8060n – independent channels PS

- After simultaneous trip, particular foil discharges to 0 properly with a proper HV scheme (resistors to ground for each electrode)
- There are significant time delays between trips of subsequent channels
- Global trip ~150ms (up to 1000 ms) later than the first trip of sparking channel
- In sparking channel, usually top and bottom side trips simultaneously, if current limits OK
- Trip in one channel may induce faster trip in another one
- **Wrong current limits may result in increase of GEM voltages!**

ALL CHANNELS TO GROUND

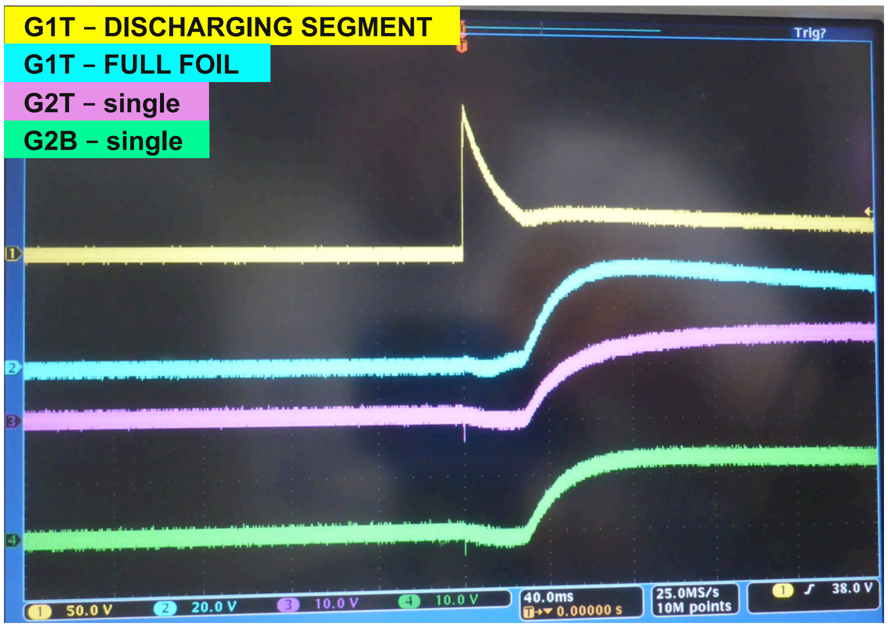


- Long discharge time
- RC ~2 s (but GEM1)
- ET3 increases first
- Slow discharge time due to non-direct grounding of the electrodes

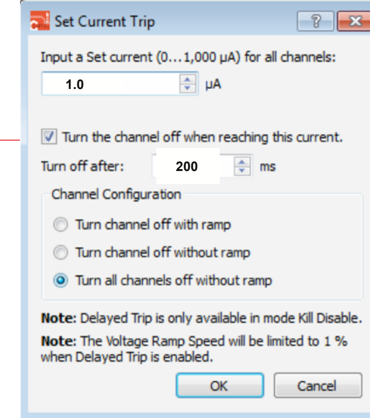


TURN ALL CHANNELS OFF WITHOUT RAMP

Internal delay time

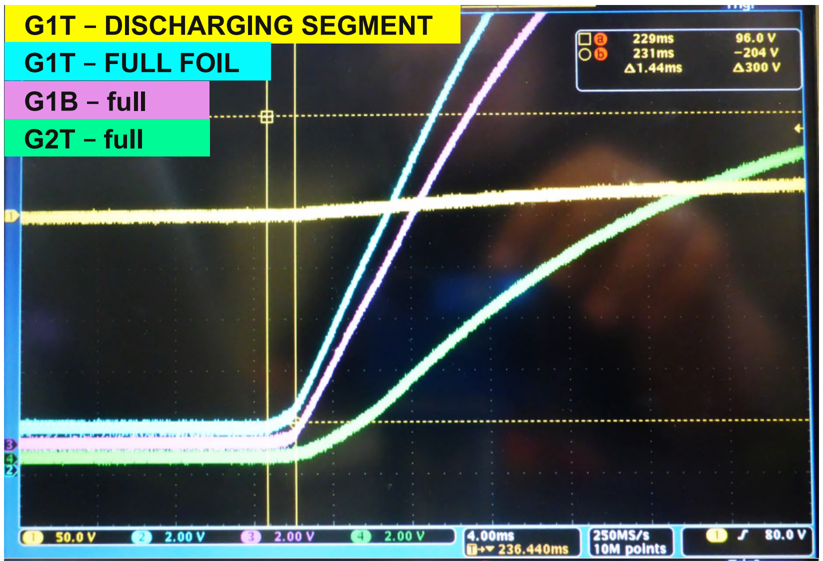


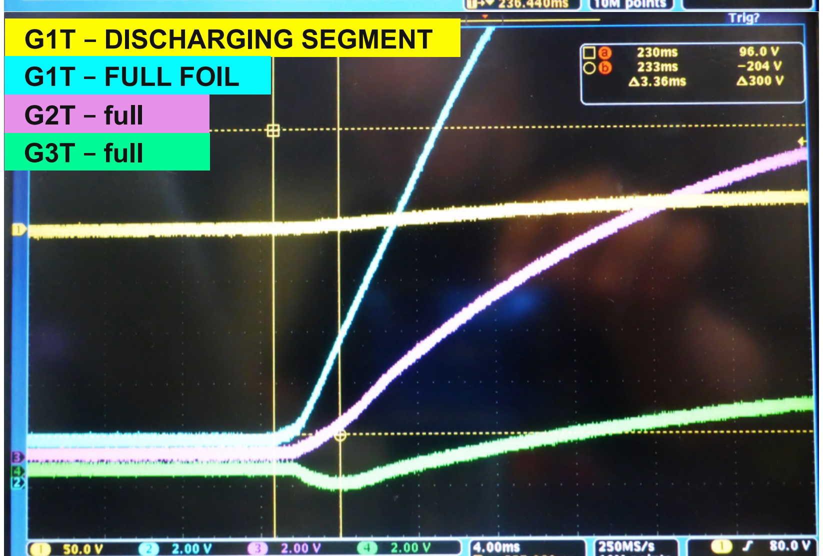
- No “software” delay (0 ms)
- Hardware delay ~20 ms
- Reaction time >> discharge time



TURN ALL CHANNELS OFF WITHOUT RAMP

Trip delays between channels



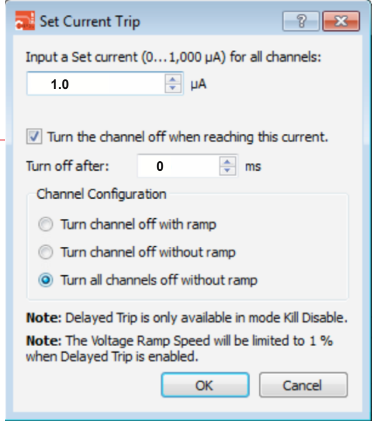


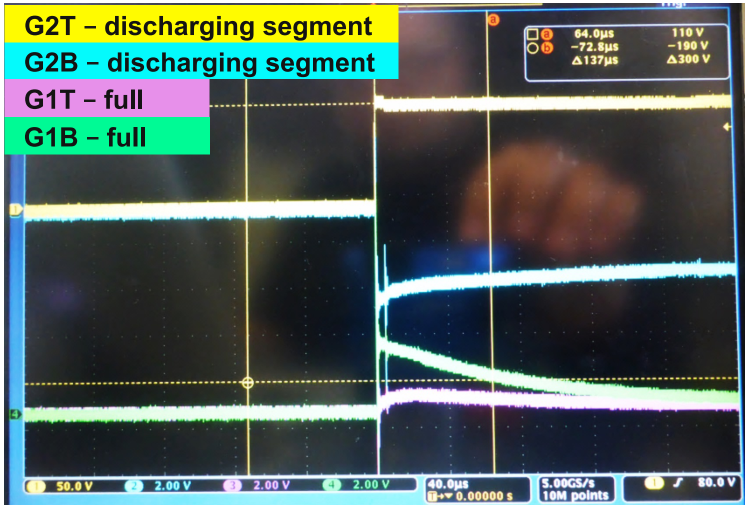
- All channels react (trip) within 0.0-1.5 ms
- Different slopes in the first moments may spoil the exact start-time location
- Different primary slopes → RC related, observed same differences many times.
- Same when tripping with different $\mathbf{I_{limit}}$ and **trip delay settings**

- GEM3T start tripping with a slight voltage increase
- Voltage to GND after ~3 ms
- Related to low E_{T3}, voltage drop across R_{dec} = 100k
- Not observed with higher E_{T3}

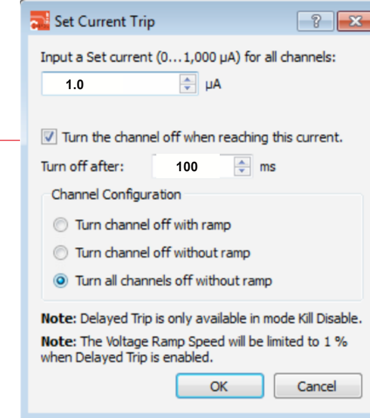
TURN ALL CHANNELS OFF WITHOUT RAMP

Search for an overvoltage –discharge moment



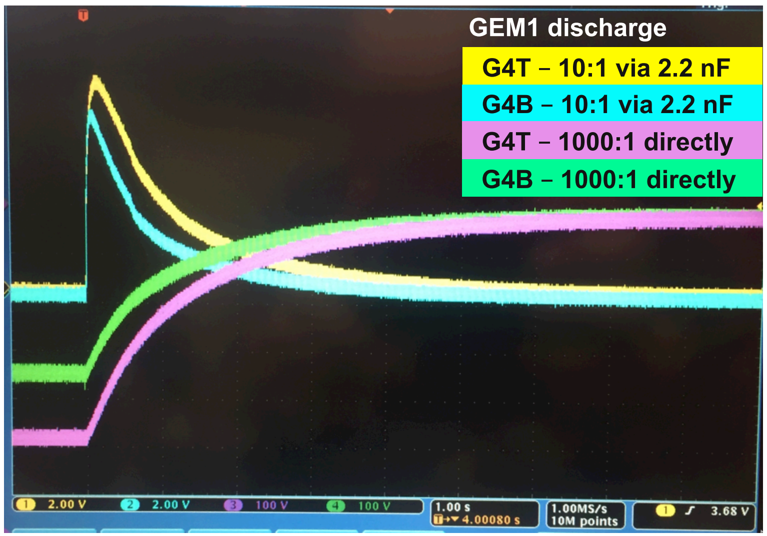


- **GEM2 relay “discharge”**
- Realistic signal amplitudes in all channels
- Possible slight overvoltage in GEM1 (~2 V for ~10 us)?
- Confirmed with SPICE; low amplitude signal on GEM1T due to reading out “full” foil
- In reality, overvoltage negligible
- Natural reaction of the system, not related to the CPS

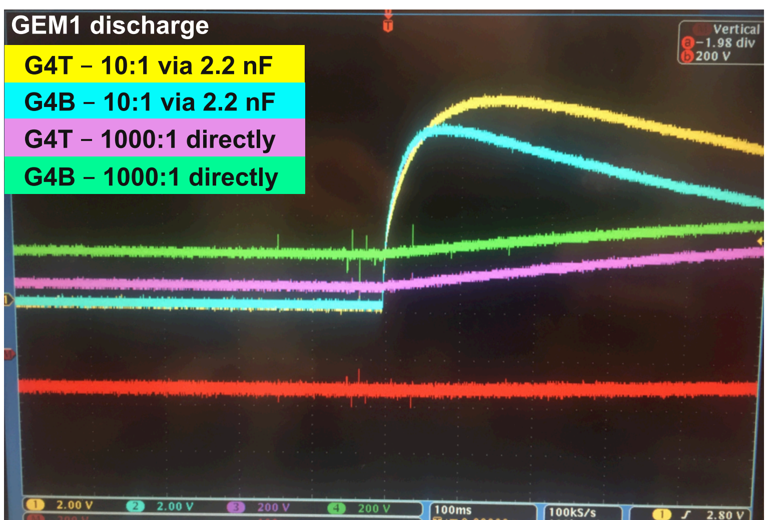


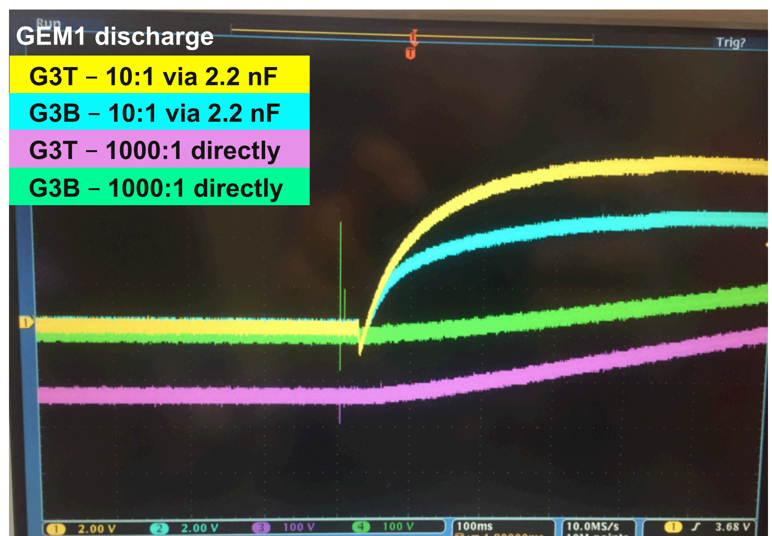
TURN ALL CHANNELS OFF WITHOUT RAMP

Search for an overvoltage – foil discharge time constants



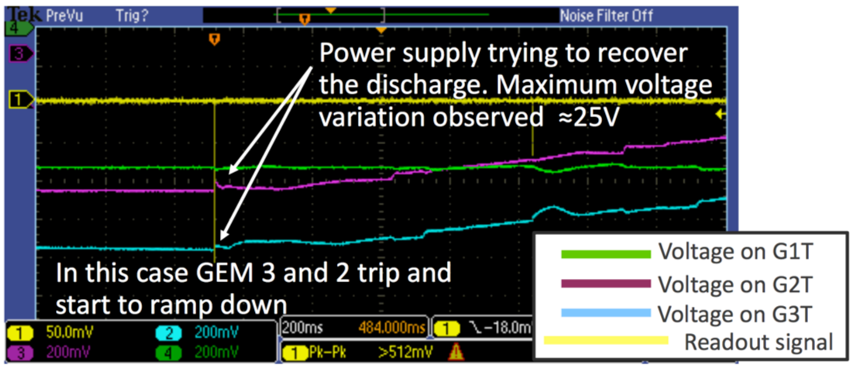
- Tripping channels studied with
  - 10:1 test probes via 2.2 nF capacitor (yellow/blue)
  - 1000:1 probes connected directly to a GEM-segment capacitor
- Tripping channel connected via 80m cables, all resistors in place
- Discharging RC ~2s
- No sign of an overvoltage on a large time scale $\mathcal{O}$(s)
- In first 50 ms of a trip, discharging speed may be higher for GEM_{Bot} which does not translate to an overvoltage



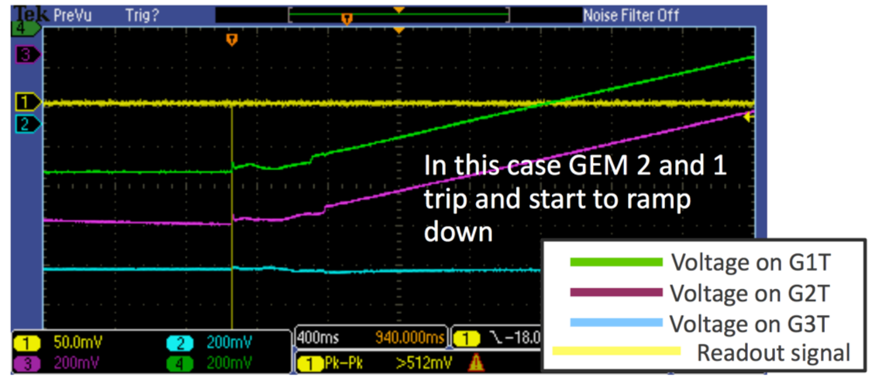


TESTING CAEN CPS

- The discharge was induced by the increase of the voltage on the top of GEM 3
- The oscilloscope was triggered with the signal from the readout plane
- We monitor the voltage on the top of each GEM



- Another case where we induced the discharge by increasing the voltage on the top of GEM 2



- Large variations in the current read in CAEN PS compare to Keithley – Nevertheless the measured values are similar
- From the discharge studies the oscillations observed on the voltage are related with the current generation mode of the power supply, which works to keep the voltage under control
- In this module it is not possible kill the voltage once the power supply trip – this will be possible on the next version of the power supply

GEM4 RESISTORS

Voltage drops and #shorts

CASCADED PS

*Load currents were scaled according to active are of GEM4

R_L (MΩ)	ΔU_{GEM4}(Nominal) – ΔU_{GEM4}(Load) [V]								
	0 shorts			1 short*	2 shorts	3 shorts	4 shorts	5 shorts	6 shorts
	10k	50k	100k	10k	10k	10k	10k	10k	10k
1	**1.5**	**2.3**	**3.2**	12.0	22.0	-	-	-	-
1.5	2.1	2.9	3.8	9.2	16.0	22.5	28.8	-	-
2.0	2.8	3.5	4.4	8.1	13.3	18.3		27.9	-
2.5	3.4	4.1	5.0	7.7	11.8	15.9			27.6
3.0	4.0	4.8	5.6	**7.6**	11.1	14.5			
4.0	5.3	6.0	6.9	7.9	**10.6**	13.2			
5.0	6.5	7.2	8.1	8.7	10.8	**12.9**			

- Voltage drops can be compensated by increasing U_{GEM} (~390 V in case of 4, 5, 6,… shorts, max 400V)
- Number of shorts given by 1mA maximum current of the PS channel

(no. Shorts * 359 V)/R_L < 1 mA

- test Cascaded PS with shorts and increased currents…performance the same?

0.5 mA RC

*Load currents were scaled according to active are of GEM4

R_L (MΩ)	ΔU_{GEM4}(Nominal) – ΔU_{GEM4}(Load) [V]									
	0 shorts			1 short*	2 shorts	3 shorts	4 shorts	5 shorts	6 shorts
	10k	50k	100k	10k	10k	10k	10k	10k	10k
1	11.5	12.3	13.2	150.6	-	-	-	-	-
1.5	12.2	12.9	13.8	119.0	175	-	-	-	-
2.0	12.8	13.6	14.4	99.5	151	-	-	-	-
2.5	13.5	14.2	15.1	86.3	134	167	-	-	-
3.0	14.1	14.8	15.7	77.0	120	151	177	-	-
4.0	15.3	16.0	16.9	64.6	101	129	153	172	-
5.0	16.6	17.3	18.2	57.1	89	114	136	154	170

- Decoupling resistor value may depend on where do we plan to put the RC (more SPICE + stability)
- **All voltages affected → have to consider all 4+4 fields! (Today only GEM4 voltages considered)**
- With a single short, GEM4 is affected substantially, additional resistance in series can compensate although not immediately (access or smart RC deisgn)
- No compensation possible if R_l/(no. shorts)<R_{GEM4}

1.0 mA RC (COMPASS-LIKE)

*Load currents were scaled according to active are of GEM4

R_L (MΩ)	ΔU_{GEM4}(Nominal) – ΔU_{GEM4}(Load) [V]								
	0 shorts			1 short*	2 shorts	3 shorts	4 shorts	5 shorts	6 shorts
	10k	50k	100k	10k	10k	10k	10k	10k	10k
1	6.5	7.2	8.1	96.5	149	-	-	-	-
1.5	7.1	7.9	8.8	72.0	117	150	-	-	-
2.0	7.8	8.5	9.4	59.0	97	127	150	170	-
2.5	8.4	9.1	10.0	50.0	84	110	132	151	167
3.0	9.0	9.7	10.6	44.6	74	98	119	136	152
4.0	10.3	11.0	11.9	37.8	61	82	99	115	131
5.0	11.5	12.2	13.1	33.6	53	71	86	101	113

- **All voltages affected → have to consider all 4+4 fields! (Today only GEM4 voltages considered)**
- With a single short, GEM4 is affected substantially, additional resistance in series can compensate although not immediately (access or smart RC deisgn)
- No compensation possible if R_l/(no. shorts)<R_{GEM4}

2.0 mA RC

ALICE

*Load currents were scaled according to active are of GEM4

R_L (MΩ)	ΔU_{GEM4}(Nominal) – ΔU_{GEM4}(Load) [V]									
	0 shorts			1 short*	2 shorts	3 shorts	4 shorts	5 shorts	6 shorts
	10k	50k	100k	10k	10k	10k	10k	10k	10k
1	4.0	4.7	5.6	58.0	98	129	153	173	-
1.5	4.6	5.3	6.2	42.4	73	98	120	137	154
2.0	5.2	5.9	6.8	34.3	59	81	99	115	130
2.5	5.8	6.6	7.5	29.6	50	68	84	100	113
3.0	6.5	7.2	8.1	26.2	44	60	75	88	101
4.0	7.7	8.4	9.3	22.8	37	49	61	72	83
5.0	9.0	9.7	10.6	20.8	32	43	53	63	72

- **All voltages affected → have to consider all 4+4 fields! (Today only GEM4 voltages considered)**
- With a single short, GEM4 is affected substantially, additional resistance in series can compensate although not immediately (access or smart RC deisgn)
- No compensation possible if R_l/(no. shorts)<R_{GEM4}

SUMMARY TABLE: R_L @ GEM4

R_L (MΩ)	0.5 mA RC			1.0 mA RC			2.0 mA RC			CASCADED		
	10k	100k	#shorts	10k	100k	#shorts	10k	100k	#shorts	10k	100k	#shorts
1.0	11.5	13.2	1	6.5	8.1	2	4.0	5.6	5	1.5	3.2	2
1.5	12.2	13.8	2	7.1	8.8	4	4.6	6.2	8	2.1	3.8	4
2.0	12.8	14.4	2	7.8	9.4	5	5.2	6.8	11	2.8	4.4	6
2.5	13.5	15.1	3	8.4	10.0	6	5.8	7.5	13	3.4	5.0	6
3.0	14.1	15.7	4	9.0	10.6	8	6.5	8.1	16	4.0	5.6	8
4.0	15.3	16.9	5	10.3	11.9	11	7.7	9.3	22	5.3	6.9	11
5.0	16.6	18.2	6	11.5	13.1	13	9.0	10.6	27	6.5	8.1	13

#shorts calculated for R_{dec} = 10k, ΔU_{GEM4} = 359 V,
for the highest numbers one should include additional current for compensation

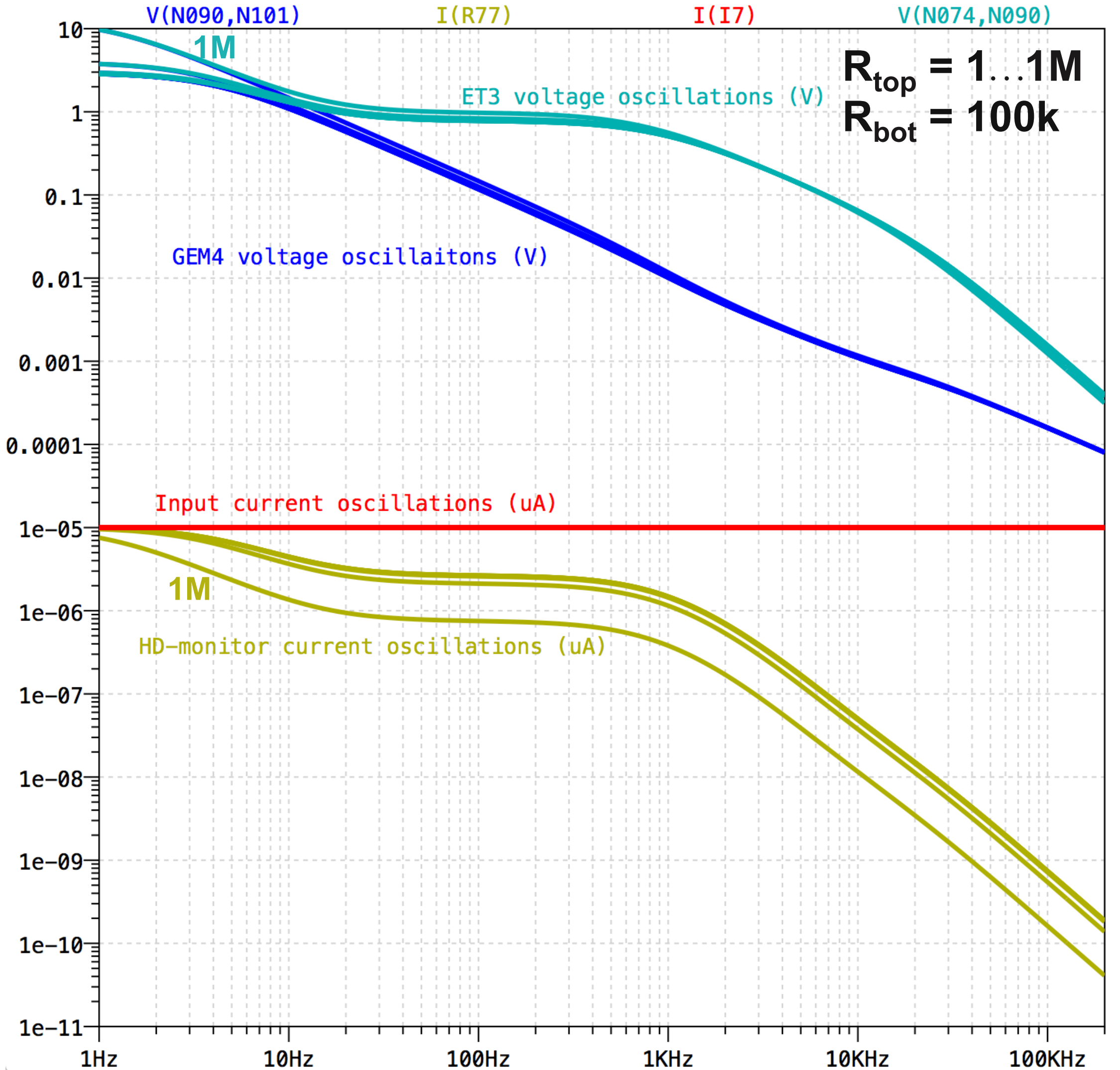
ALICE

SUMMARY TABLE (AVERAGE)

Numbers from SPICE

	0.5 mA VD		1.0 mA VD		2.0 mA VD		CASCADED	
	10k	100k	10k	100k	10k	100k	10k	100k
ΔV_{G1} [V]	+4.4	+4.3	+2.2	+2.2	+1.1	+1.1	0	0
U_{T1} [V]	+11.2	+11.2	+5.6	+5.6	+2.8	+2.8	0	0
ΔV_{G2} [V]	+3.7	+3.7	+1.8	+1.9	+0.9	+0.9	0	0
U_{T2} [V]	+11.2	+11.2	+5.6	+5.6	+2.8	+2.8	0	0
ΔV_{G3} [V]	+5.1	+5.1	+2.4	+2.6	+1.3	+1.3	0	0
U_{T3} [V]	**+7.0**	**+9.0**	**+6.9**	**+8.9**	**+6.8**	**+8.8**	**+6.7**	**+8.7**
ΔV_{G4} [V]	-16.0	-17.6	-11.2	-12.9	-9	-10.6	-6.7	-8.3
U_{IND} [V]	-26.6	-27.0	-13.4	-13.8	-6.7	-7.1	0	-0.5

DAMPING EFFICIENCY



DAMPING EFFICIENCY