Studies on RPC with Semi Insulating -GaAs electrodes

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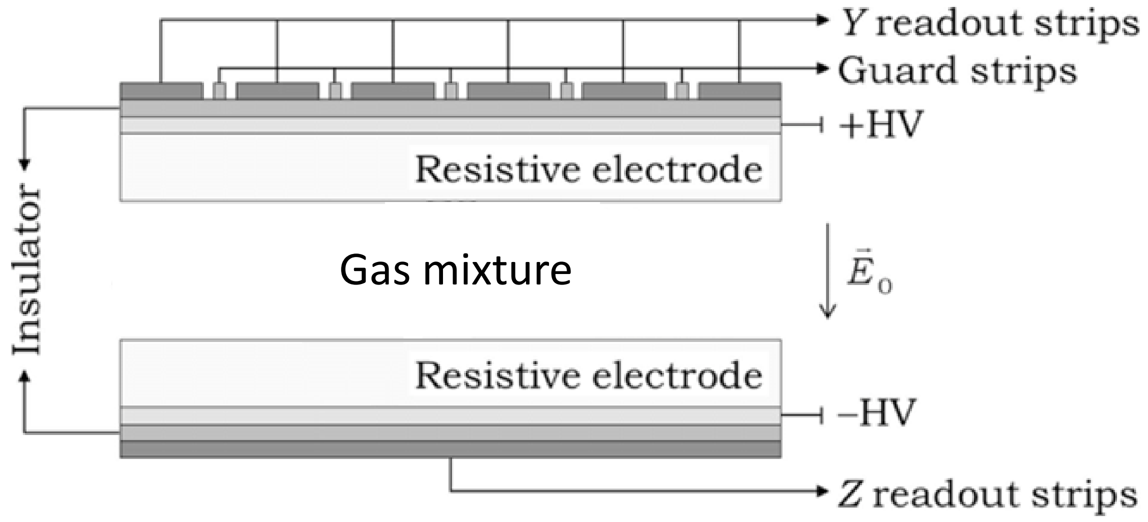
Outline

- RPC detector limiting factors
- Prototypes design
- Recent results: Linearity Response, Time Response & Rate Capability
- New tests: H4-Gif++
- Results
- ongoing tests @H8
- Conclusions

The Resistive Plate Chamber Detector

- Time resolution ~350 ps (1mm gas gap)
- Spatial resolution ~100 µm (0.8 mm strip pitch)
- Intrinsic Rate Capability ~10 kHz/cm^2 (2fC threshold)
- Cost ~2 k€/m^2 (depending on the readout granularity)
- Detector lifetime above 0.3 C/cm^2
- Detector thickness ~1 cm



PERSPECTIVES AND LIMITING FACTORS

✓High Rate

$$V_{gas} = V_{gen} - \rho d\bar{Q}\phi$$

- The improvements on the FE electronics and detector design shift the intrinsic rate capability up to ~7 kHz/cm^2
- The HPL electrodes guarantee stable operation up to a total integrated charge of 0.3 C/cm^2 **--> Effective rate capability significantly limited by both experiment lifetime and background radiation**

A new material immune to the ageing effect should improve the effective rate capability of a factor ten, just with $10^{10}\ \Omega cm$ resistivity

(Semi Insulating Gallium Arsenide Wafers): Low resistivity, Crystal structure, Thin electrode

[T. Franke et al. "Potential of RPCs for tracking", NIM Section A, Volume 508]
[A. Rocchi et al. **RPC detectors with semiconductive electrodes: efficiency and time resolution measurements**, 2019, JINST, 14, 12, C12005, proceeding for the XIV Workshop on RPC 2018]
[A. Rocchi et al. Linearity and rate capability measurements of RPC with semiinsulating crystalline electrodes operating in avalanche mode, Dicember 2020,JINST, Vol. 15, C12004,proceeding for the XV Workshop on RPC 2020.]
[A. Rocchi et al. Development of gaseous particle detectors based on semiconductive plate electrodes, November 2018, Il Nuovo Cimento C, Vol. 3, Art. 100 October 2023]

+

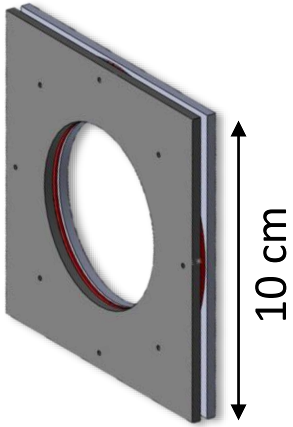
Low noise FE electronics < 4-6 fC

[R. Cardarelli et al., Performance of RPCs and diamond detectors using a new very fast low noise preamplfier, Jinst, 8 (2013)]

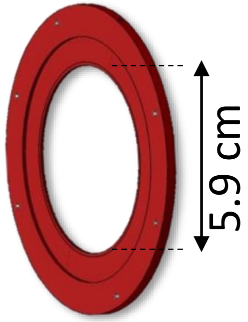
PROTOTYPE DESIGN AND FE-ELECTRONICS

Gas inlet ø 2 mm -> ø 0.6 mm

Wafers holder

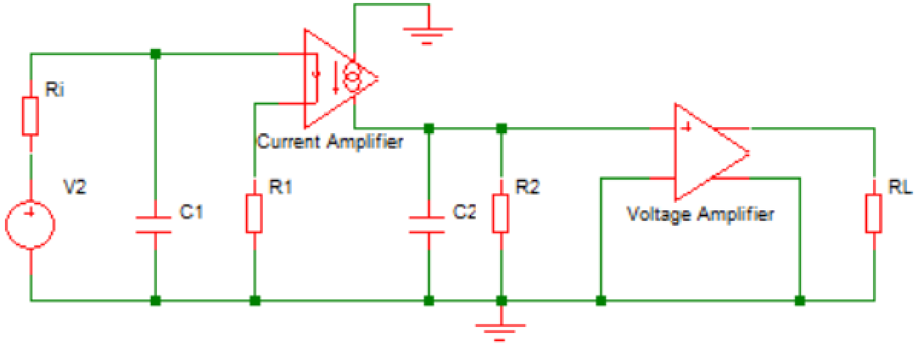


Wafers spacer 1 mm



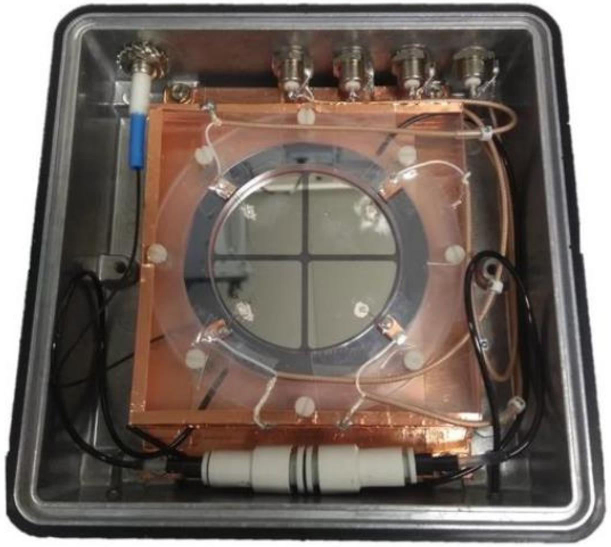
[R. Cardarelli et al, "Performance of RPCs and diamond detectors using a new very fast low noise preamplifier"]

Voltage supply	3–5 Volt
Sensitivity	2–4 mV/fC
Noise (independent from detector)	4000 e^- RMS
Input impedance	100–50 Ohm
B.W.	10–100 MHz
Power consumption	10 mW/ch
Rise time $\delta(t)$ input	300–600 ps
Radiation hardness	1 Mrad, 10^{13} n cm^{-2}



Material	Semi Insulating undoped GaAs
Thickness	640 – 643; μm
Diameter	3″
Resistivity	$1.4 \times 10^8\ \Omega cm$
Surface treatment	both polished
Growth method	VGF
Orientation	$(100) \pm 0.01°$
Mobility	5300 cm^2/Vs

Thanks to Prof. M. Lucci (RM2) for the GaAs metallization



Wafers sputtering holder

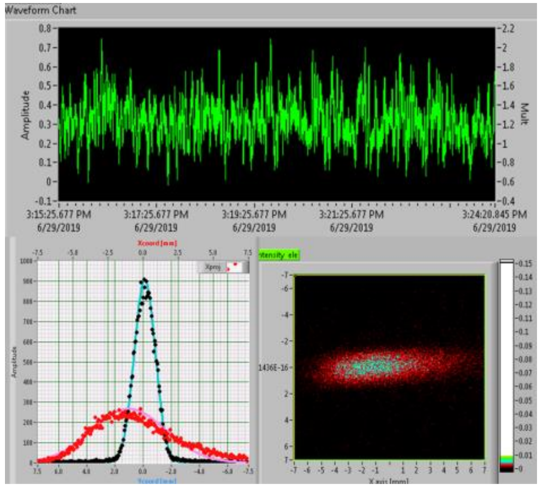
Costs: 100€/Wafer

FIRST RESULTS AT THE INFN-LNF BEAM TEST FACILITY (2019-2020)

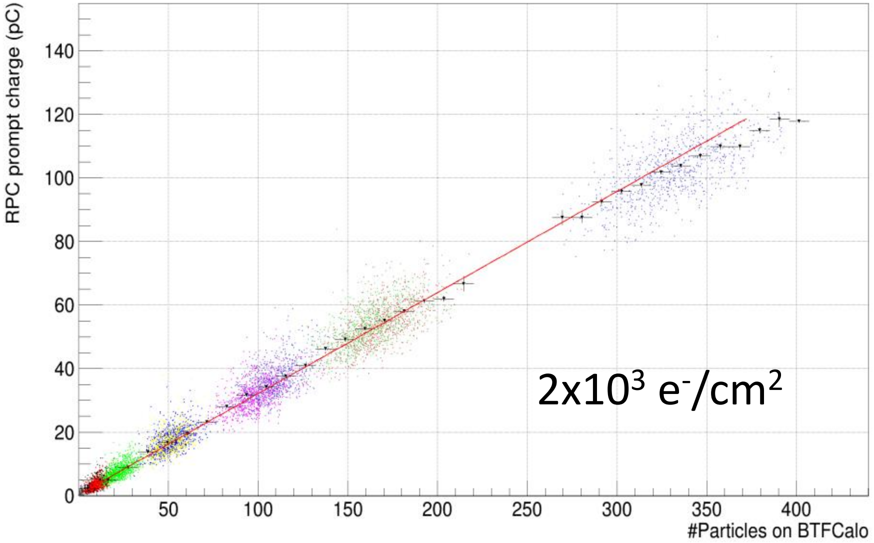
[B. Buonomo, G. Mazzitelli and P. Valente "Performance and Upgrade of the DAFNE Beam Test Facility (BTF)"]

beam properties:

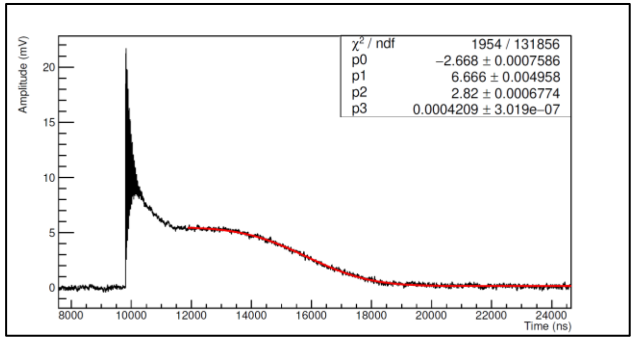
- Gaussian shape,
- ~ 20Hz bunch frequency
- 250 MeV electrons;
- intensity up to 400 e^-/bunch;



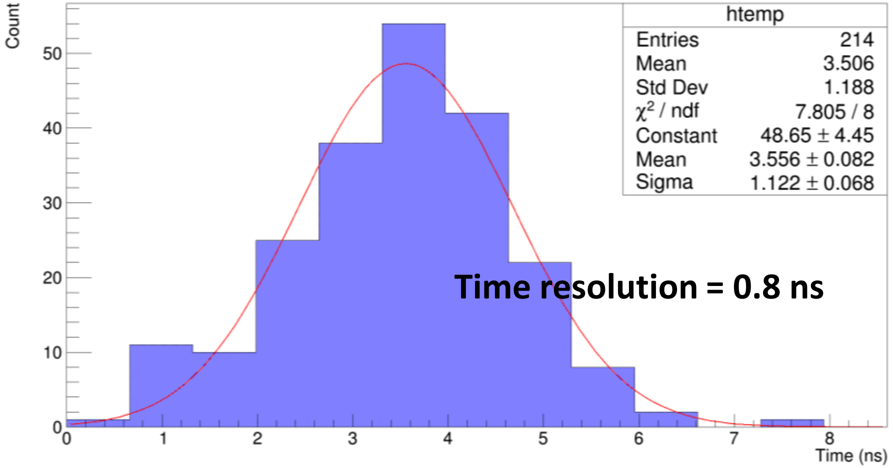
Linearity response in avalanche mode 1 mm gas gap

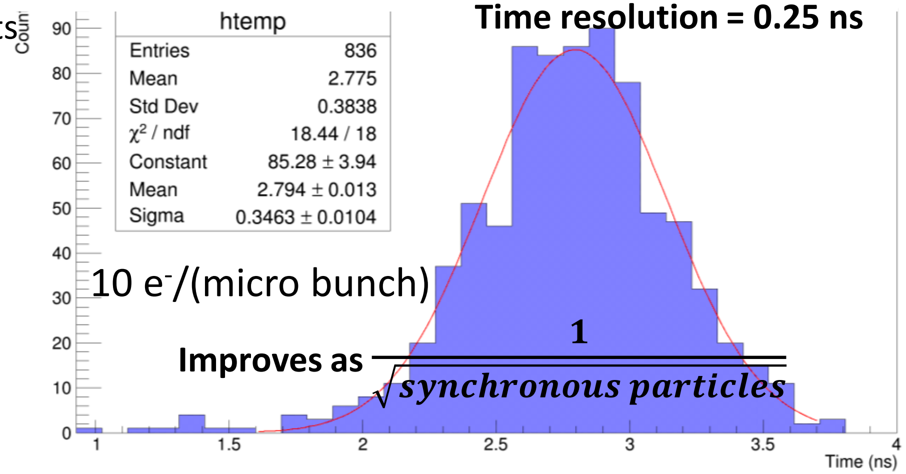


Total signal, read-out directly from contacts on 1 kΩ from bunched e^-



Time resolution with bunched particles





[A. Rocchi et al "Linearity and rate capability measurements of RPC with semi-insulating crystalline electrodes operating in avalanche mode"]

NEW SETUP @ H4-GIF++ TEST AREA (2019-21)

D. Pfeiffer et al, The radiation field in the Gamma Irradiation Facility GIF++ at CERN.

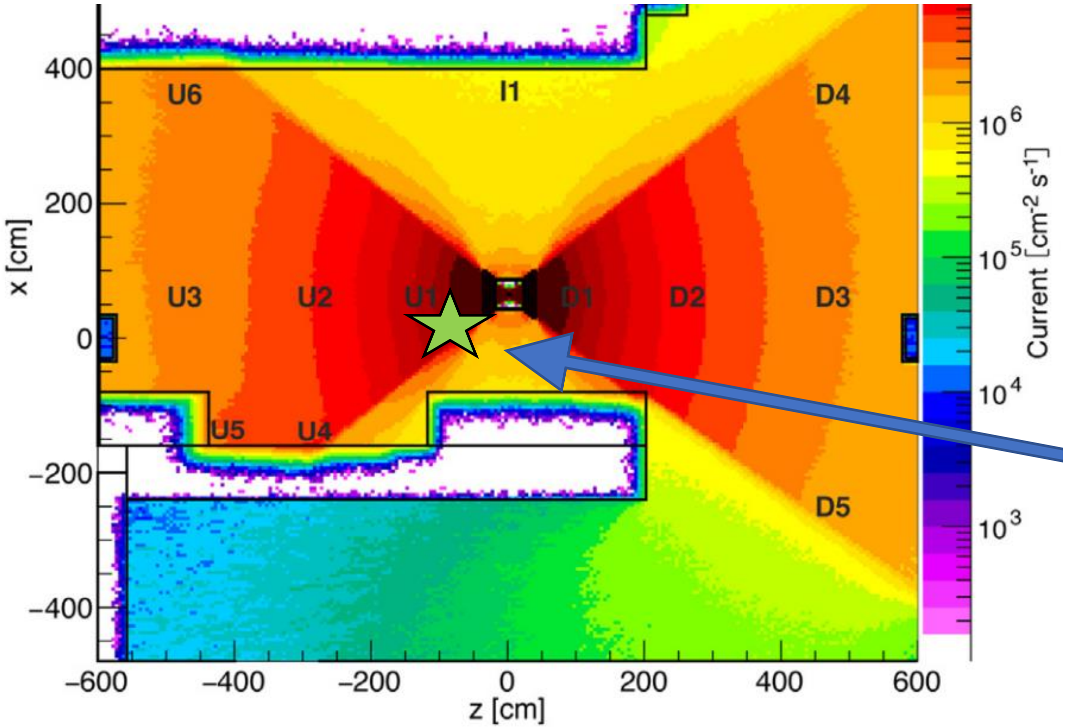
- 14.9 TBq ^{137}Cs source (662 keV photons 33% - 54%)
- Constant photon current in the xy plane for 662 keV photons
- 180 GeV/c muons beam

The setup was placed in the upstream **region U1**

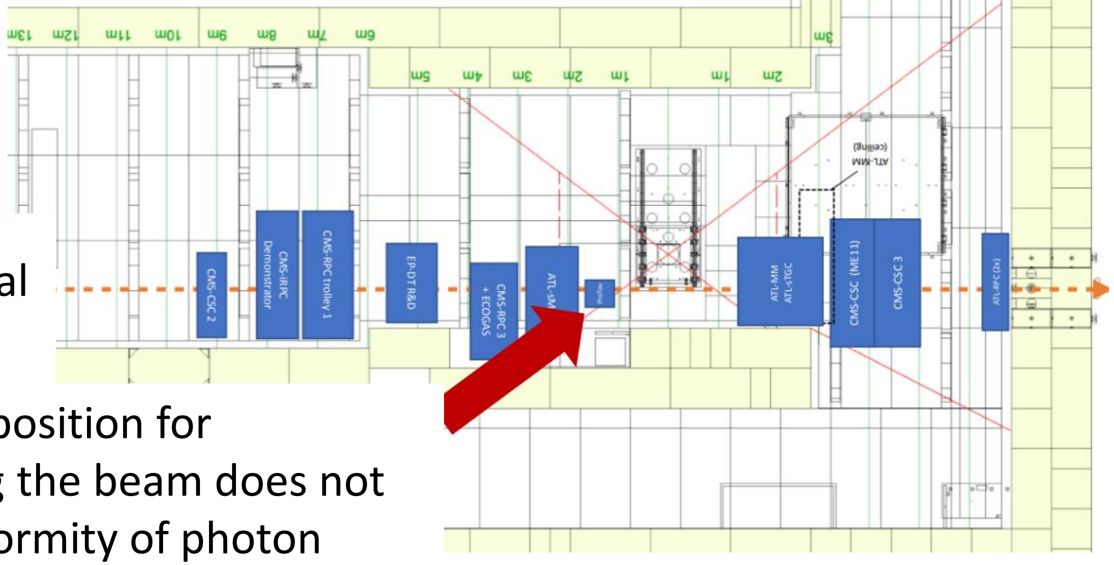
-> **Maximum photon current $4.3 \times 10^7 \frac{photons}{cm^2 s}$**

No photon converter on the electrode surface

->RPC photon efficiency $\sim 10^{-3}$ (to be measured for GaAs RPC) -> maximum photons counting rate $\sim 40\ \mathrm{kHz/cm^2}$



Experimental setup



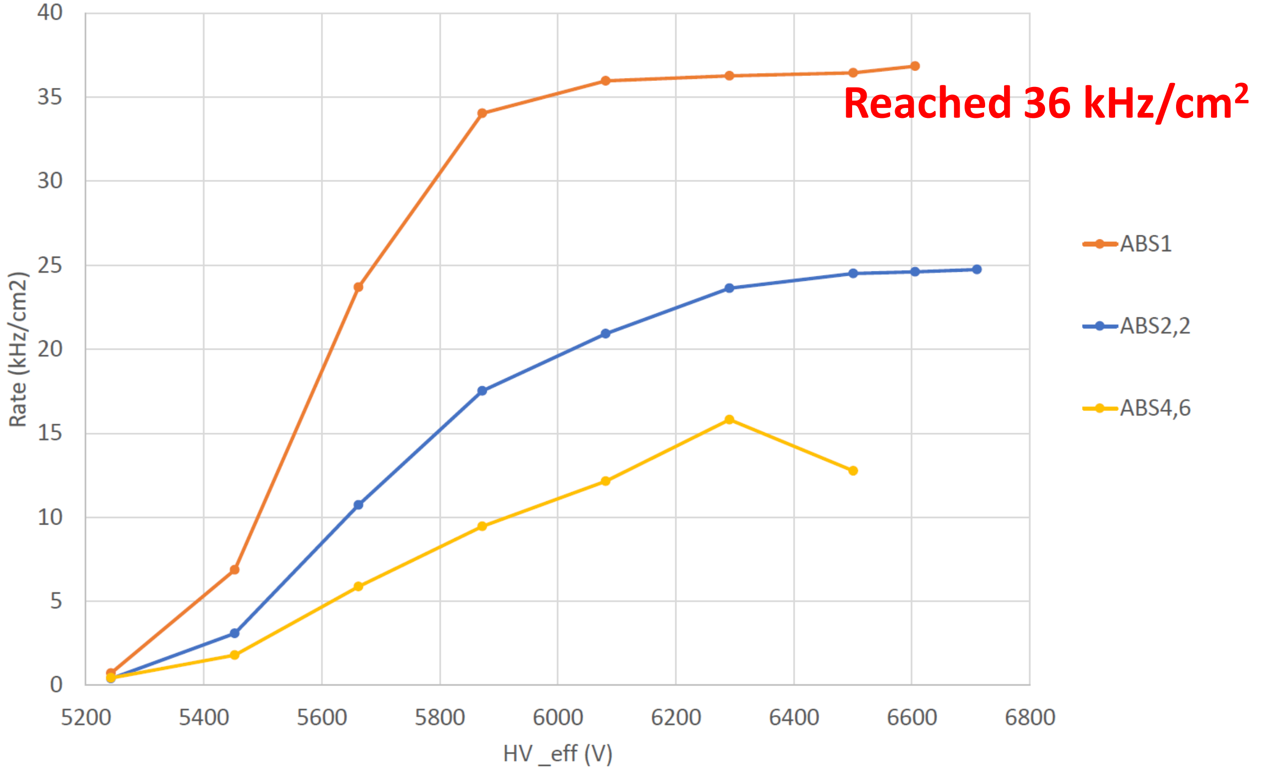
The lateral position for intercepting the beam does not ensure uniformity of photon current over the active area

FIRST RESULTS @ GIF++

Counting rates for different filter absorption factors

- photon flux decreases as the ABS increases

- efficiency knee point previously measured at 5850V with threshold set to 35 mV on 50 Ω.

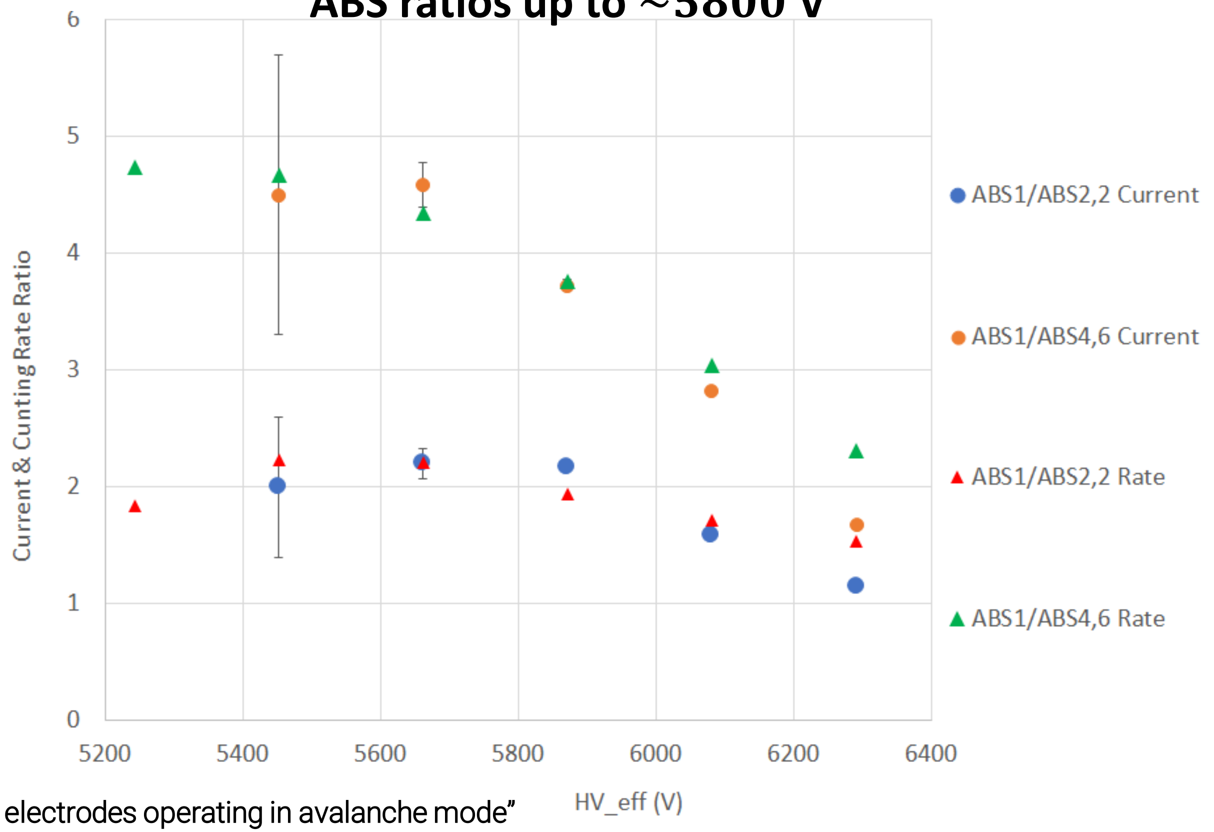


Expected ratios (without saturation)

$$\frac{I_1}{I_{2.2}} = \frac{\phi_1 * \bar{Q}}{\phi_{2.2} * \bar{Q}} = \frac{\phi_1}{\phi_{2.2}} = \frac{2.2 * \phi_{2.2}}{\phi_{2.2}} = 2.2$$

$$\frac{I_1}{I_{4.6}} = \frac{\phi_1 * \bar{Q}}{\phi_{4.6} * \bar{Q}} = \frac{\phi_1}{\phi_{4.6}} = \frac{4.6 * \phi_{4.6}}{\phi_{4.6}} = 4.6$$

Counting rate and current ratios are consistent with the ABS ratios up to ~5800 V



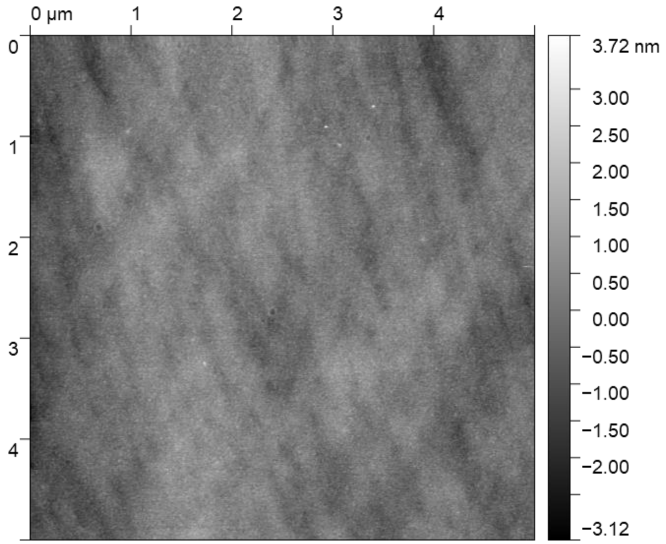
A. Rocchi et al "Linearity and rate capability measurements of RPC with semi-insulating crystalline electrodes operating in avalanche mode"

FIRST AGING OBSERVATION

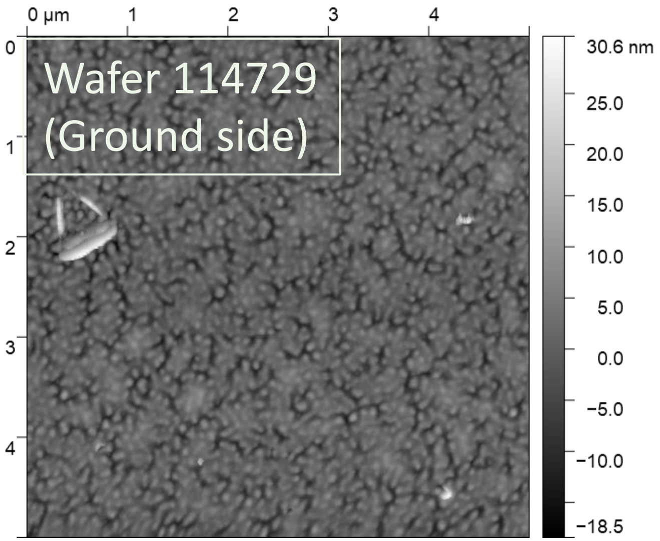
The surfaces of two used wafers have been analyzed with the Atomic Force Microscopy

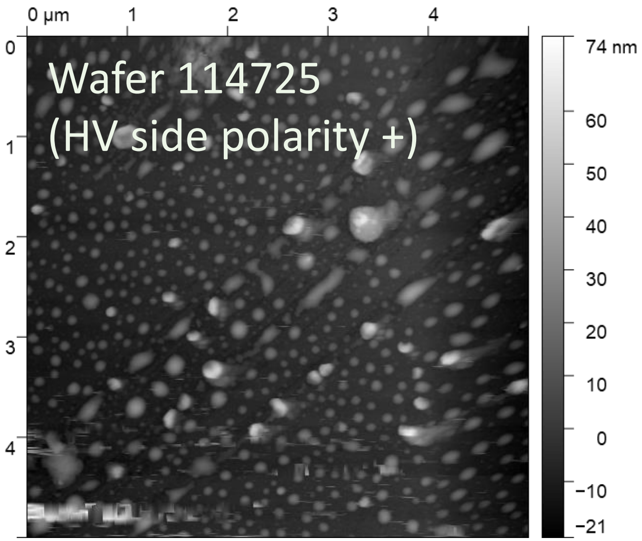
- Microstructures 58-96 nm height with different shapes were found at the center of the wafer
- The edge of the wafer (out of the detector active region) shows a uniform flat surface

Edge



Center



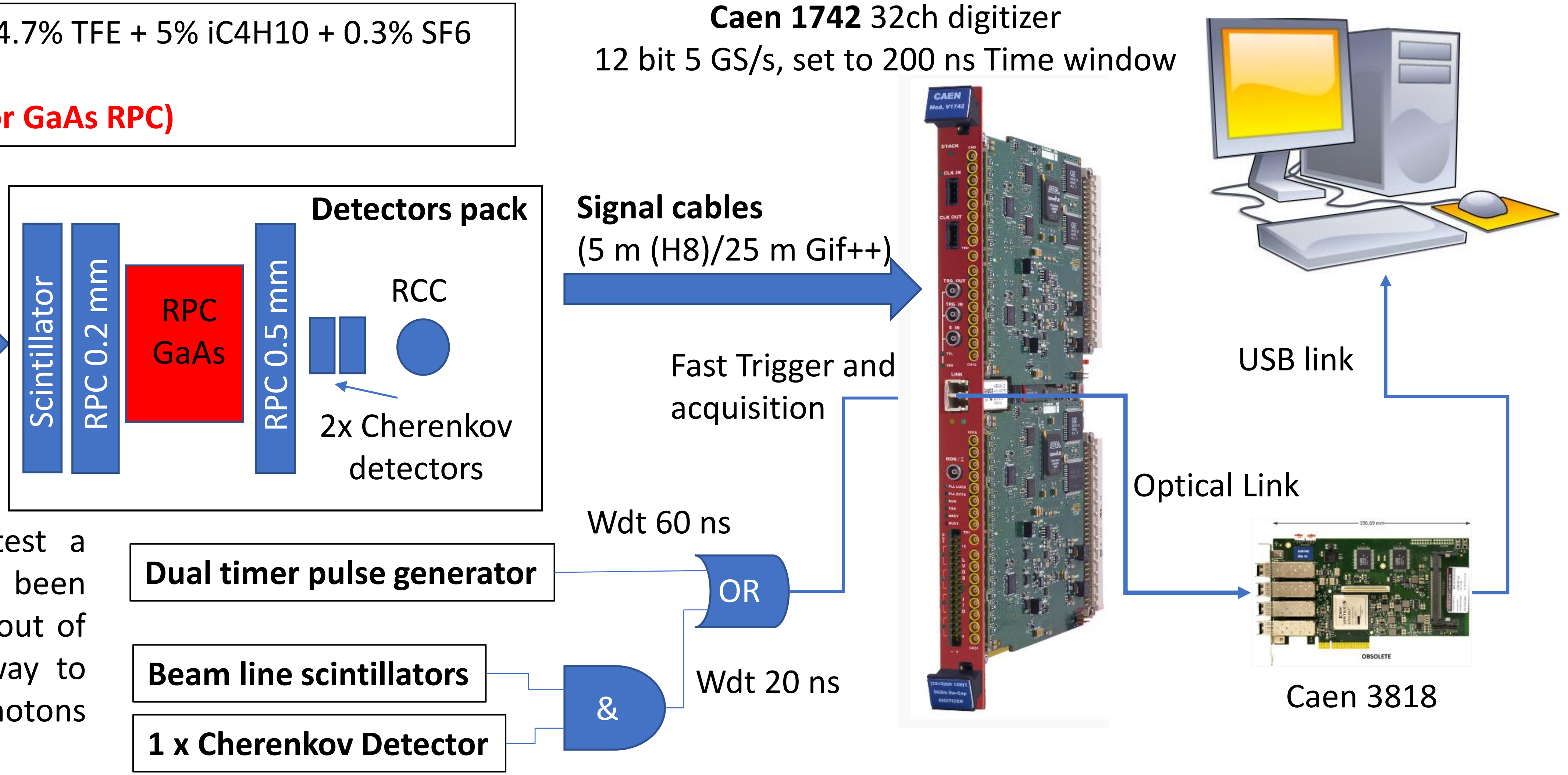


Thanks to Prof. Ernesto Placidi (RM2)

A. Rocchi et al "Linearity and rate capability measurements of RPC with semi-insulating crystalline electrodes operating in avalanche mode"

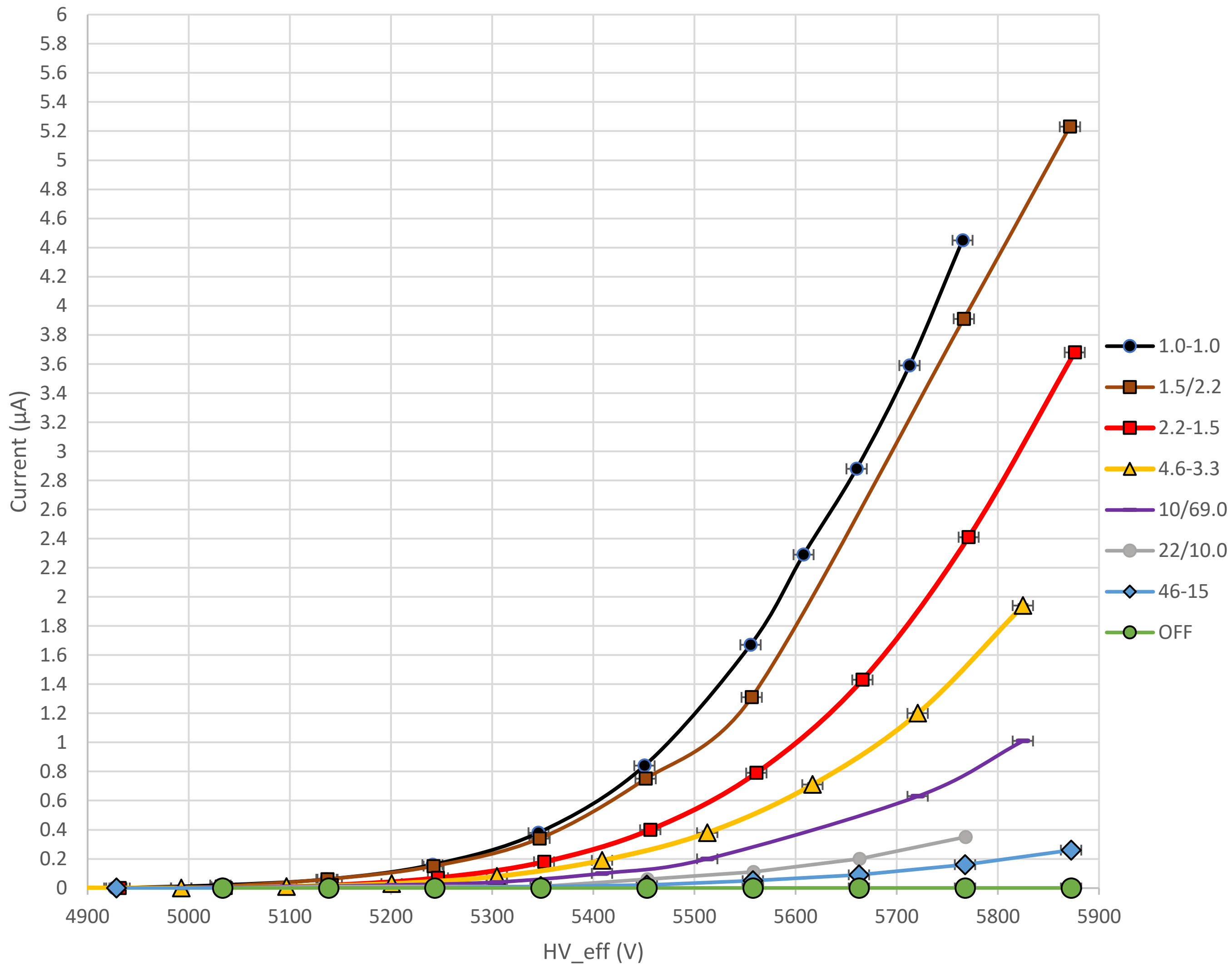
EXPERIMENTAL SETUP

Gas Mixture: 94.7% TFE + 5% iC4H10 + 0.3% SF6
Line 1 -> Wet
Line 2 -> Dry (for GaAs RPC)



For the Gif++ test a Dual timer has been used to acquire out of spill events in way to measure the photons counting rates

CURRENTS VS ATTENUATION

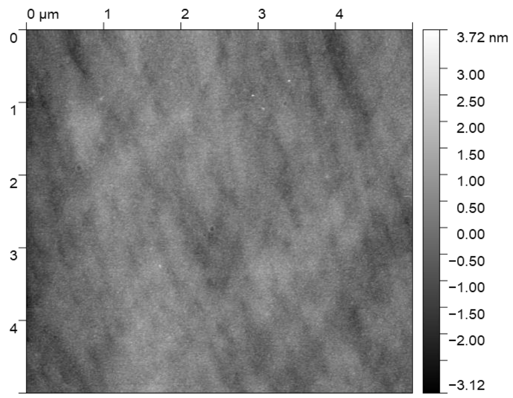


The first point that stands out when observing the current absorbed by the detector, is the absence of ohmic component and the negligible random counting rate (fraction of Hz/cm^2)

Without photon background the current is $(0 \pm 0.01)\ \mu A$ up to the higher HV working point !

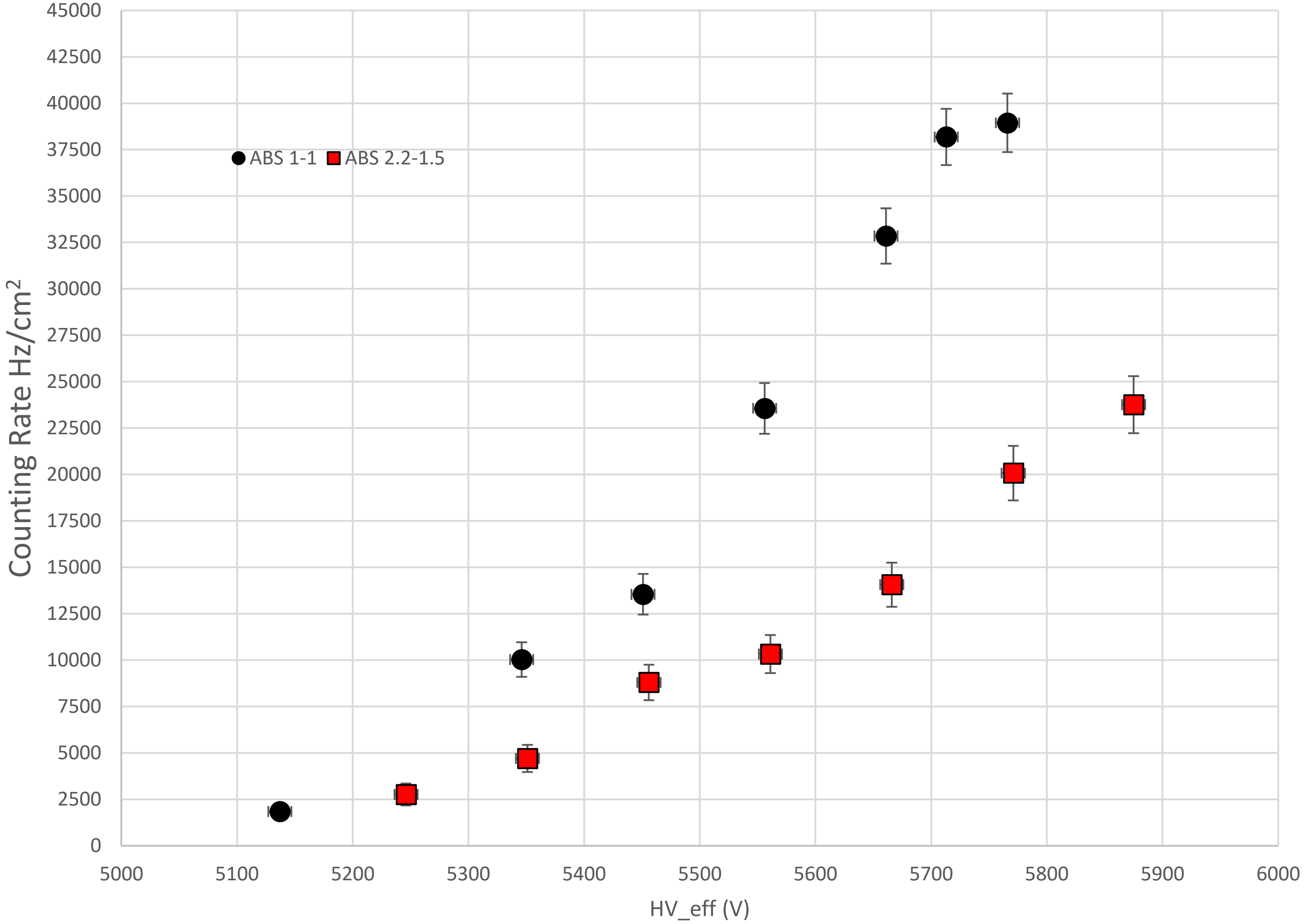
Also with photon background, the current is not measurable with the experimental sensitivity for voltage lower then 5000 V

This behavior is probably linked to the excellent quality of the spacer, but above all to the surface structure of the electrode



COUNTING RATES VS ATTENUATION

The gamma efficiency should be approximately 10^{-3}

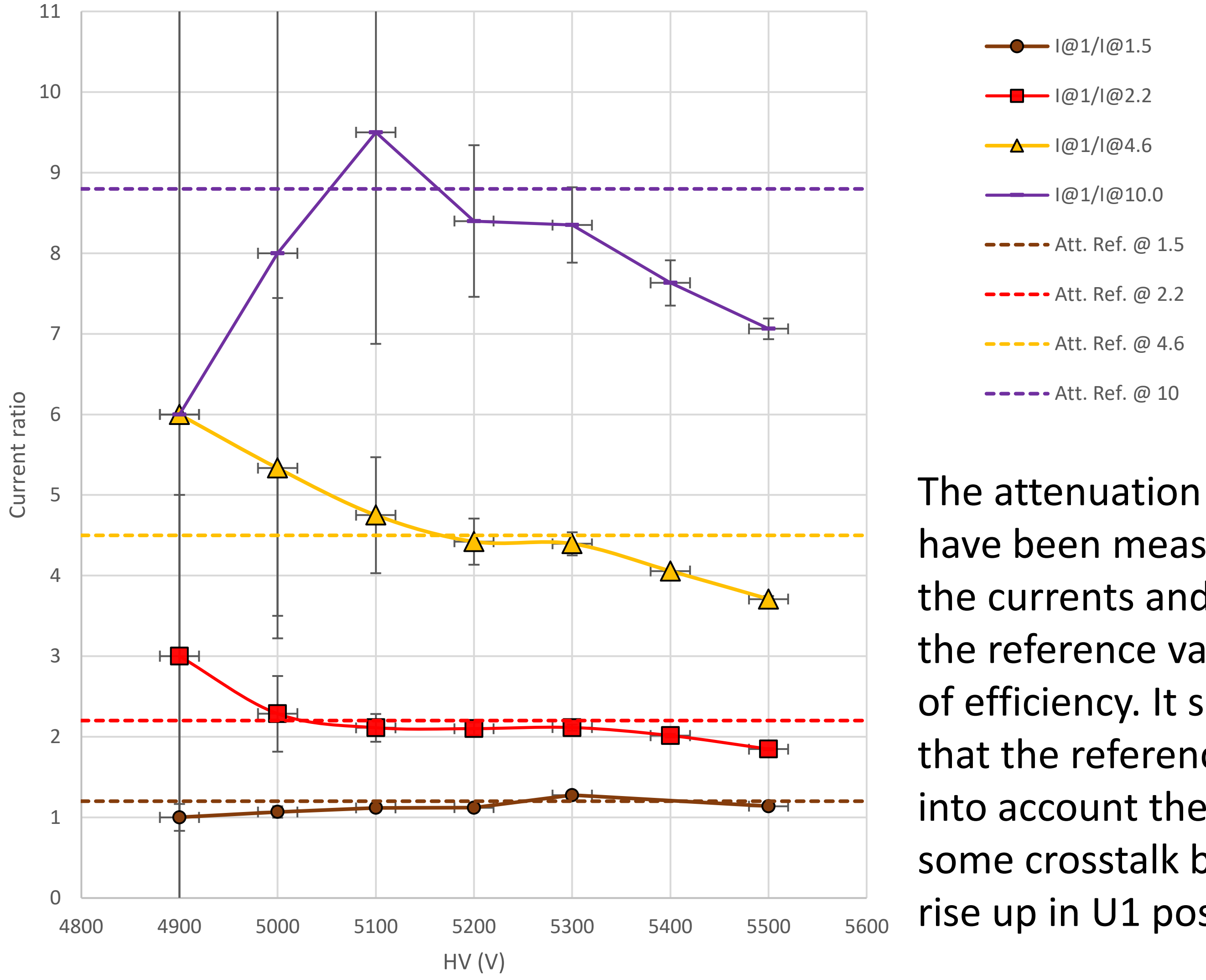


The counting rate has been measured acquiring random counts out of spills. Each time window is 200 ns so about 3000 events have been integrated for each HV working point.

The maximum counting rate measured is about 39 kHz/cm^2 in a 4.3 x 10^7 photons/cm^{2}s radiation field

consistent with that measured with the old prototype in the DownStream position (36 kHz/cm^2) at almost same distance from the source. In that case the signals were just discriminated and counted

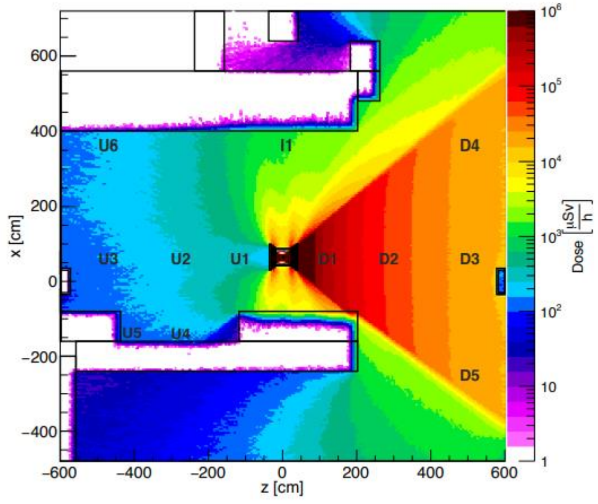
ATTENUATION FACTORS MEASUREMENTS



	Measured attenuation		
Attenuation of 662 keV gammas	Filter Combination	Dose [mSv/h]	Attenuation Dose
1	A1 B1 C1	470.00	-
1.5	A1 B2 C1	400.00	1.2
2.2	A1 B1 C2	211.00	2.2
4.6	A1 B1 C3	105.00	4.5
10	A2 B1 C1	55.00	8.8
100	A3 B1 C1	6.50	72.3
100	A1 B3 C1	6.20	75.8
464	A1 B3 C3	1.59	295.6
4642	A2 B3 C3	0.22	2156.0
46420	A3 B3 C3	0.05	9400.0

Table 3. Filter attenuation of downstream filters measured in D1. The upstream filters were closed.

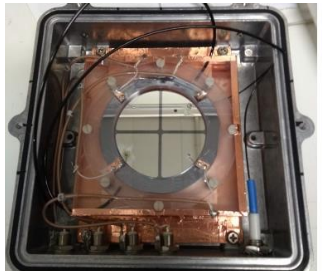
The attenuation factors of the source have been measured by the ratios of the currents and are consistent with the reference values up to the knee of efficiency. It should be emphasized that the reference values only take into account the 662 keV ranges and some crosstalk between US and DS rise up in U1 position

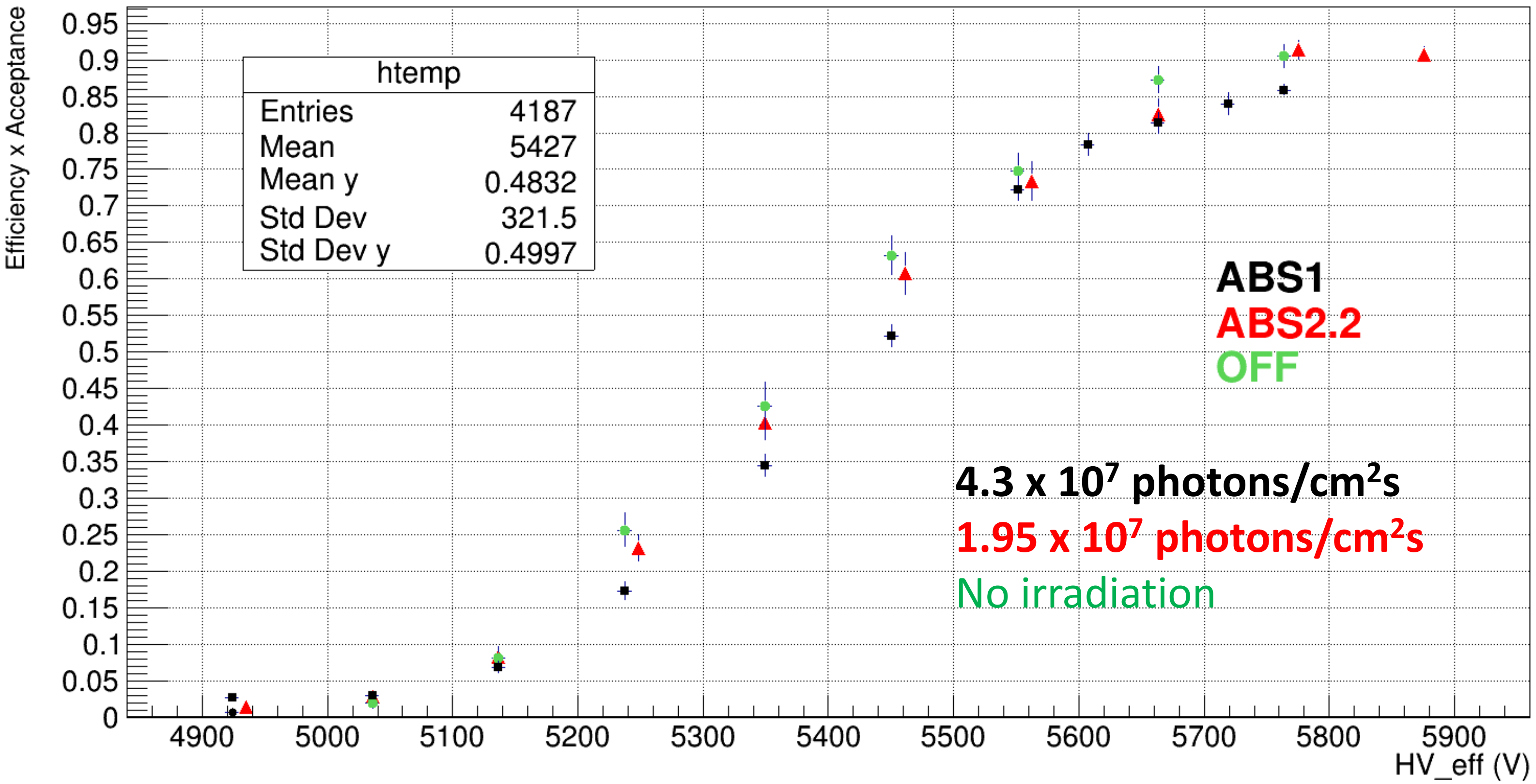


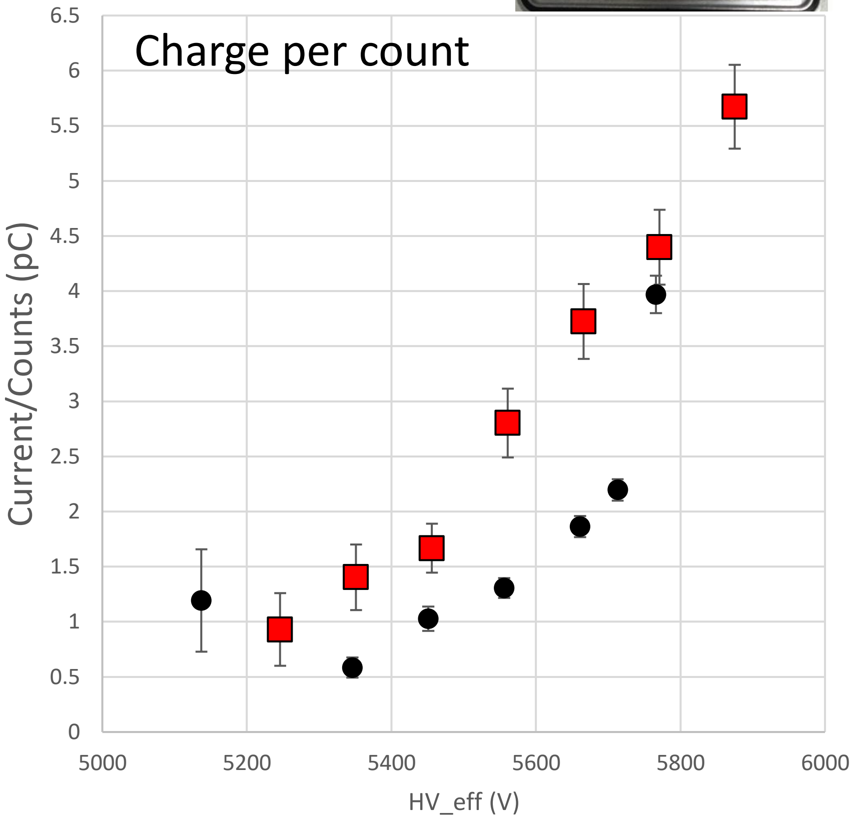
(a) DS open/US closed

EFFICIENCY AND CHARGE PER COUNT

The efficiency curves are very close in the three different conditions. A slight shift of the curve at maximum rate is consistent with a significant reduction in the average charge per count. From the trend of the average charge per count it is possible to understand how important the sensitivity of the FE electronics is to obtain this result. The acceptance Is probably limited by the pickup design.





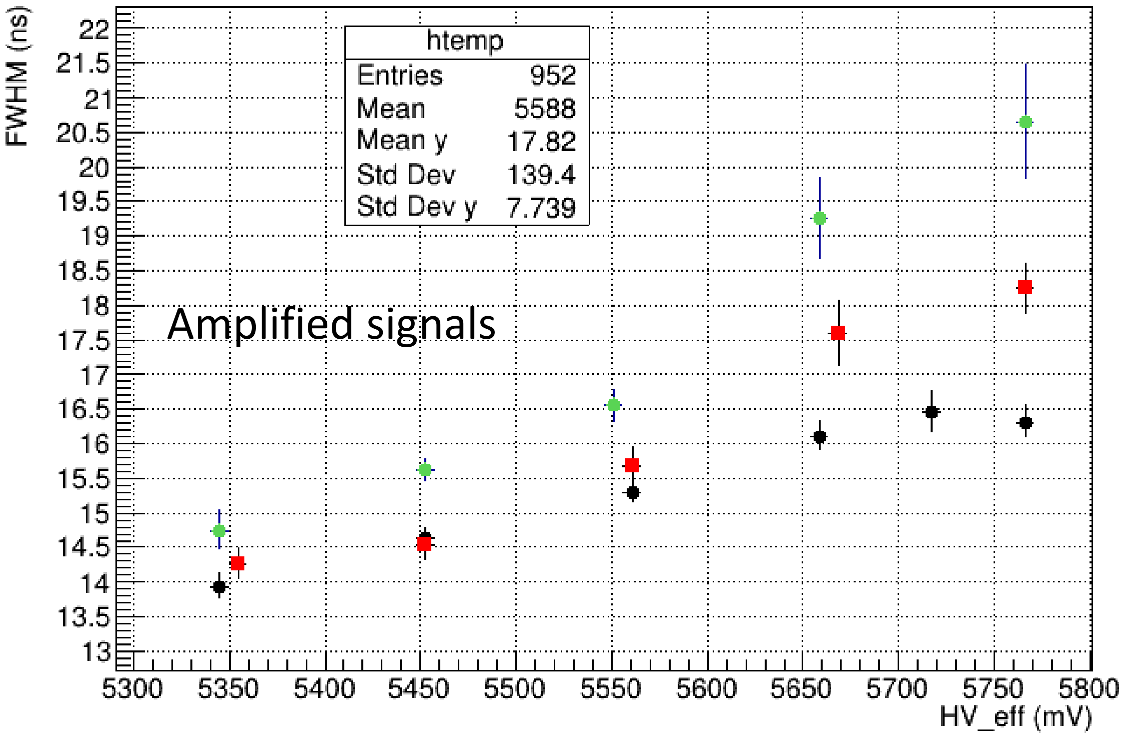


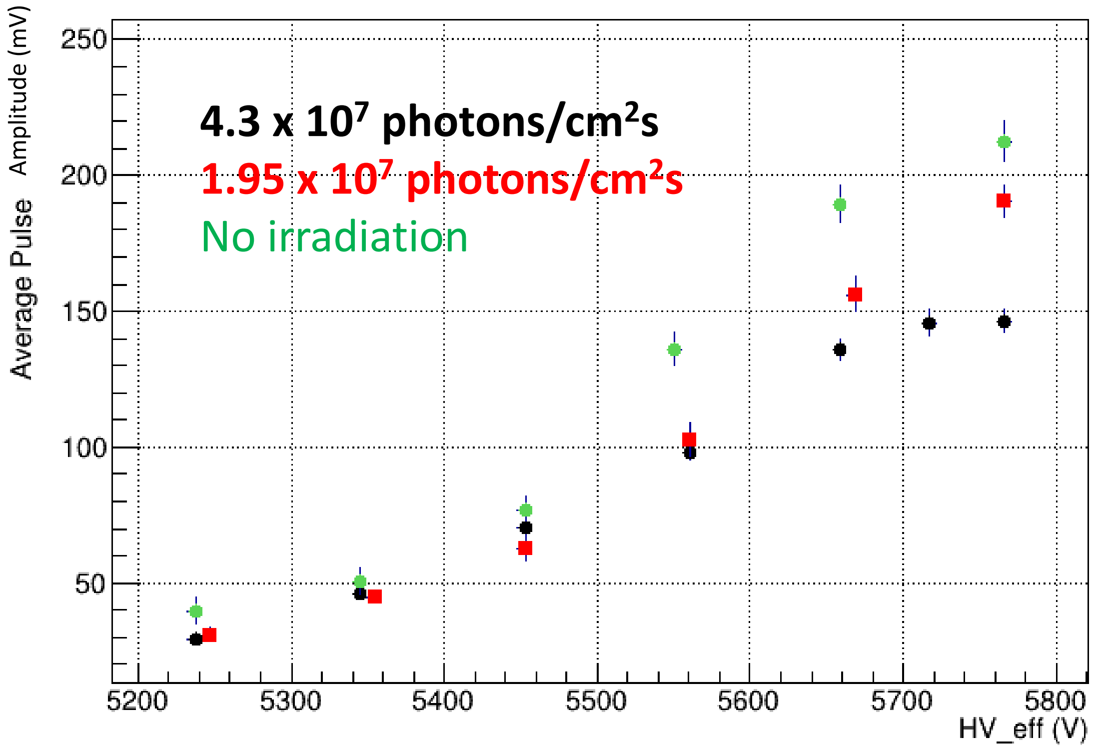
PULSE SHAPE PARAMETERS

Despite the small impact on the efficiency performance, the signal attenuation with high photon irradiation is clearly visible from the signal parameters.

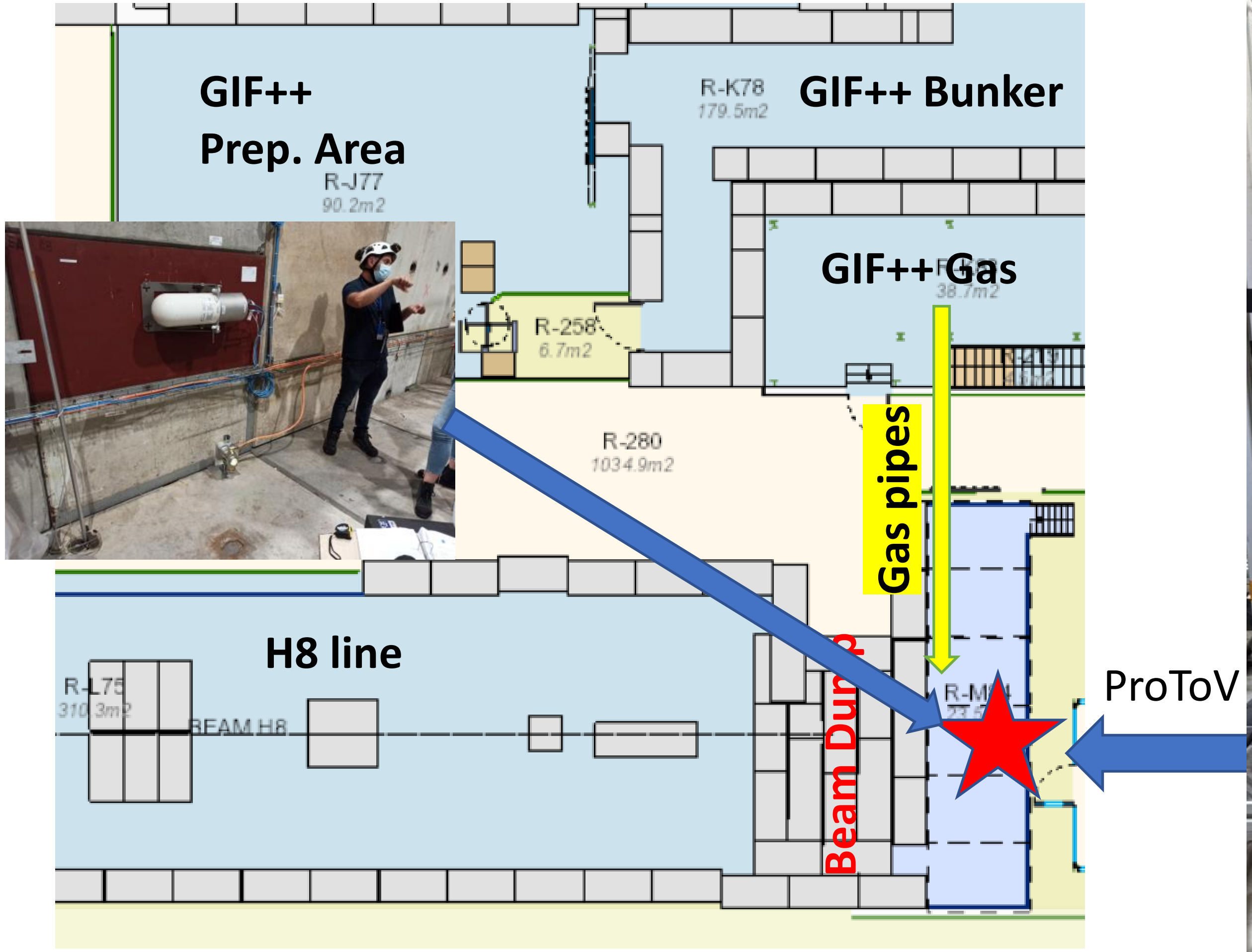
A reduction in both the average amplitude and the Full Width Half Maximum is observed.

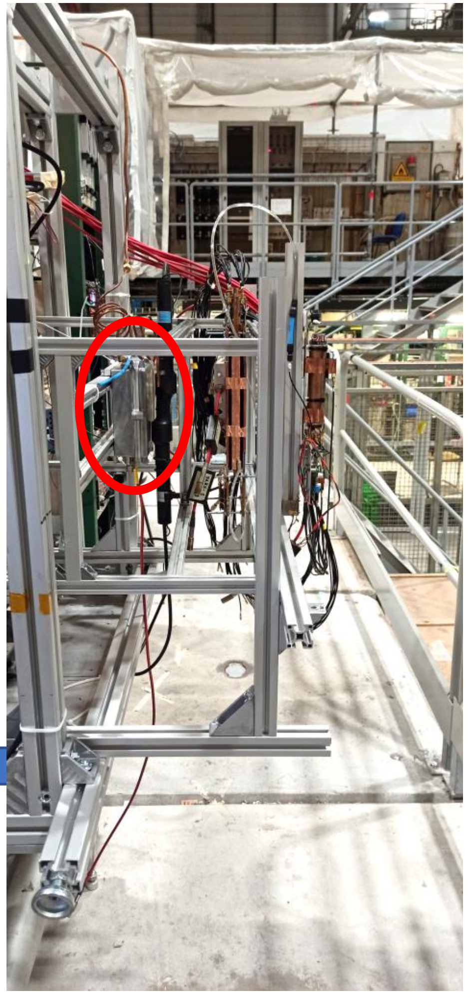
This means that the FE-Electronics threshold is low enough to allow the discrimination of almost all the signals in the charge distribution and shows how important is to have a FE threshold one order of magnitude lower as respect to the mean charge in an RPC detector.





SETUP @ H8 BEAM DUMP PLATFORM (2021)



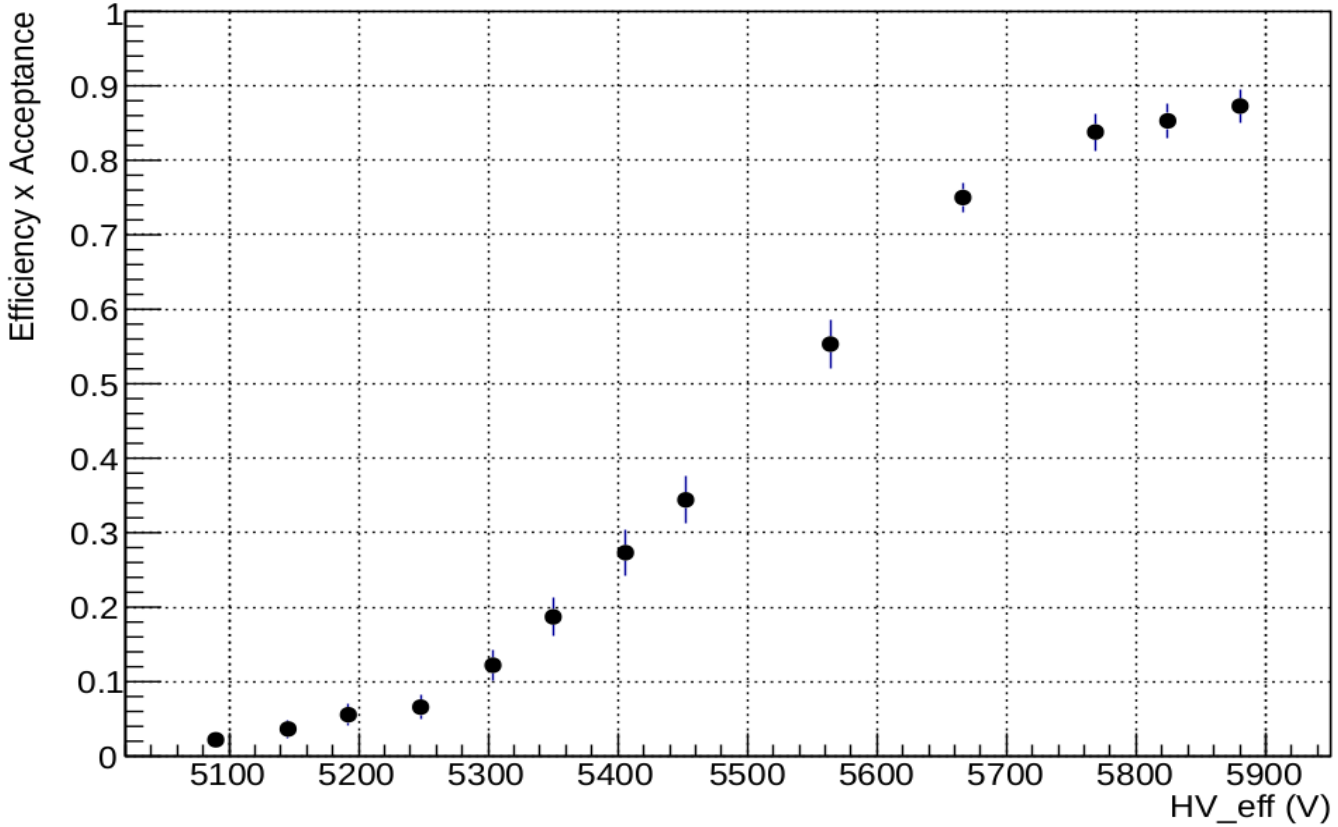


2 gas pipes shared with CMS-RPC

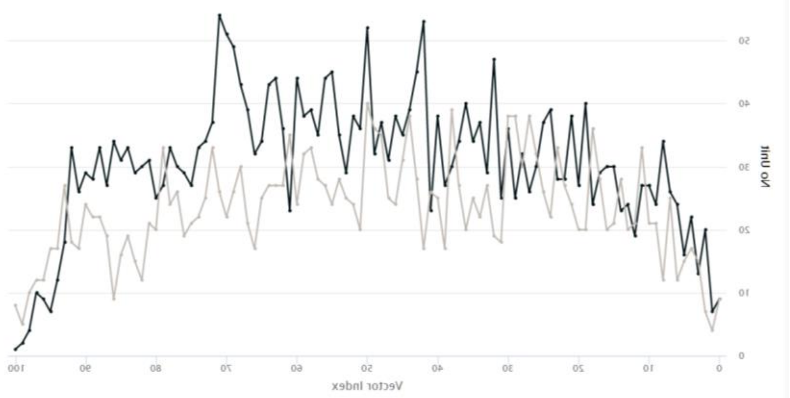
- Wet Standard mixture
- Dry Standard mixture

SETUP @ H8 BEAM DUMP PLATFORM

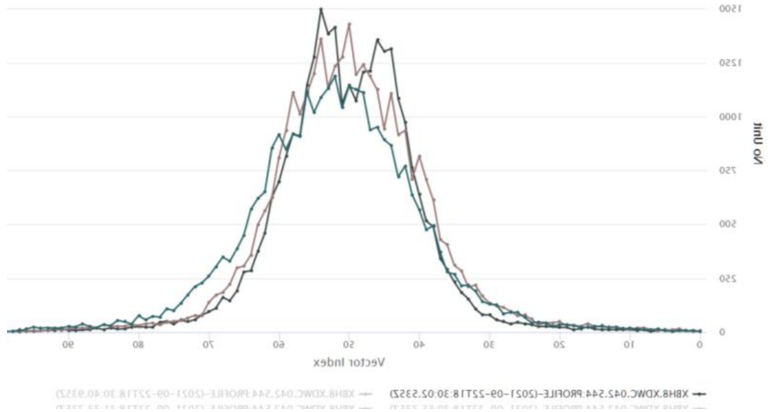
Even the preliminary test on the H8 line shows an acceptance limit, probably due to the layout of the readout pick-up / HV electrode.
The beam profile is still larger as respect to the tested prototypes
-> we are working on new trigger detectors for medium size



Two beams possibility in this position:



Residual from dumped secondary pions beam



tertiary muon beam
About 8 cm FWHM before the dump

The GaAs RPC in the DRD1 Collaboration

Anyone interested in contributing to this activity is welcome!

Many activities still pending:

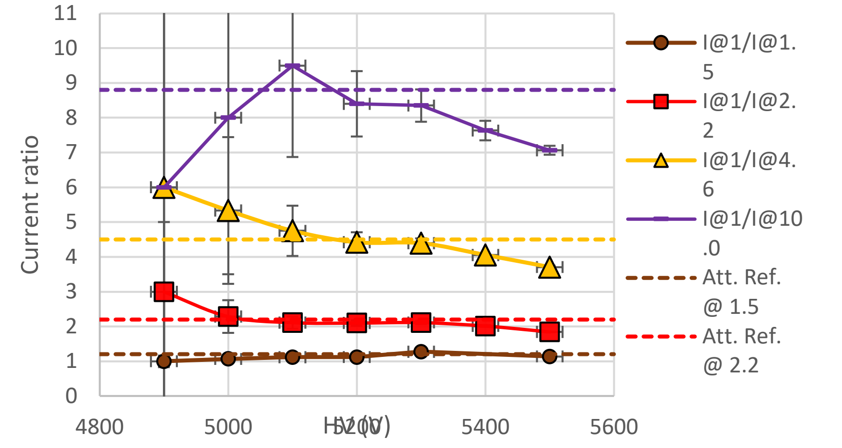
- material aging study
- study of the interactions between gas and material
- optimization of the gas mixture
- study of the multigap configuration
- development of new FE electronics
- study of surface treatments
- Study of sensitivity to gamma and neutrons

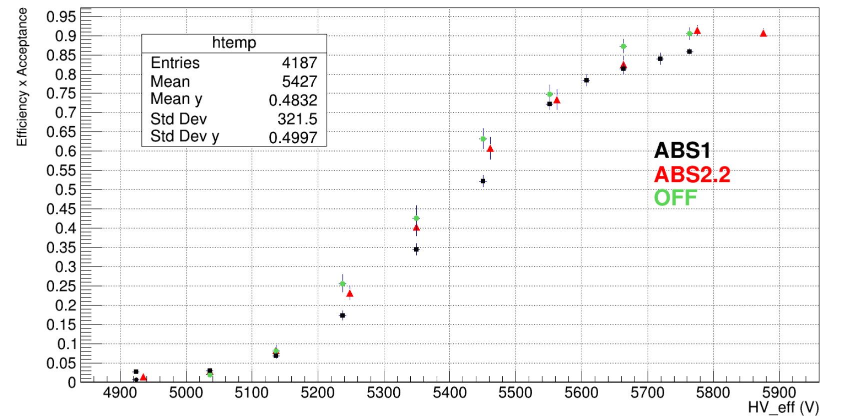
Optimization:

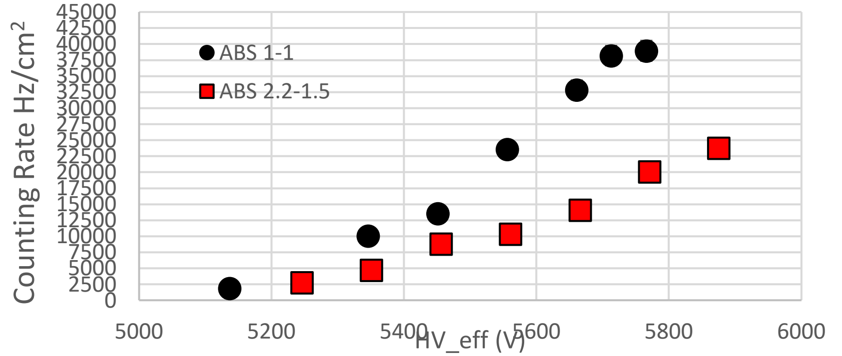
- engineering the mechanical structure
- New design and simulation of read-out/contacts pickup

Instrumentation and infrastructure

- Sputtering machine for the readout electrodes
- Atomic force microscopy (AFM) and X-ray photoelectron spectroscopy (XPS) for surface characterization
- X-ray gun for very high-rate test







Conclusions

The efforts made in recent years on this activity have led to impressive results:

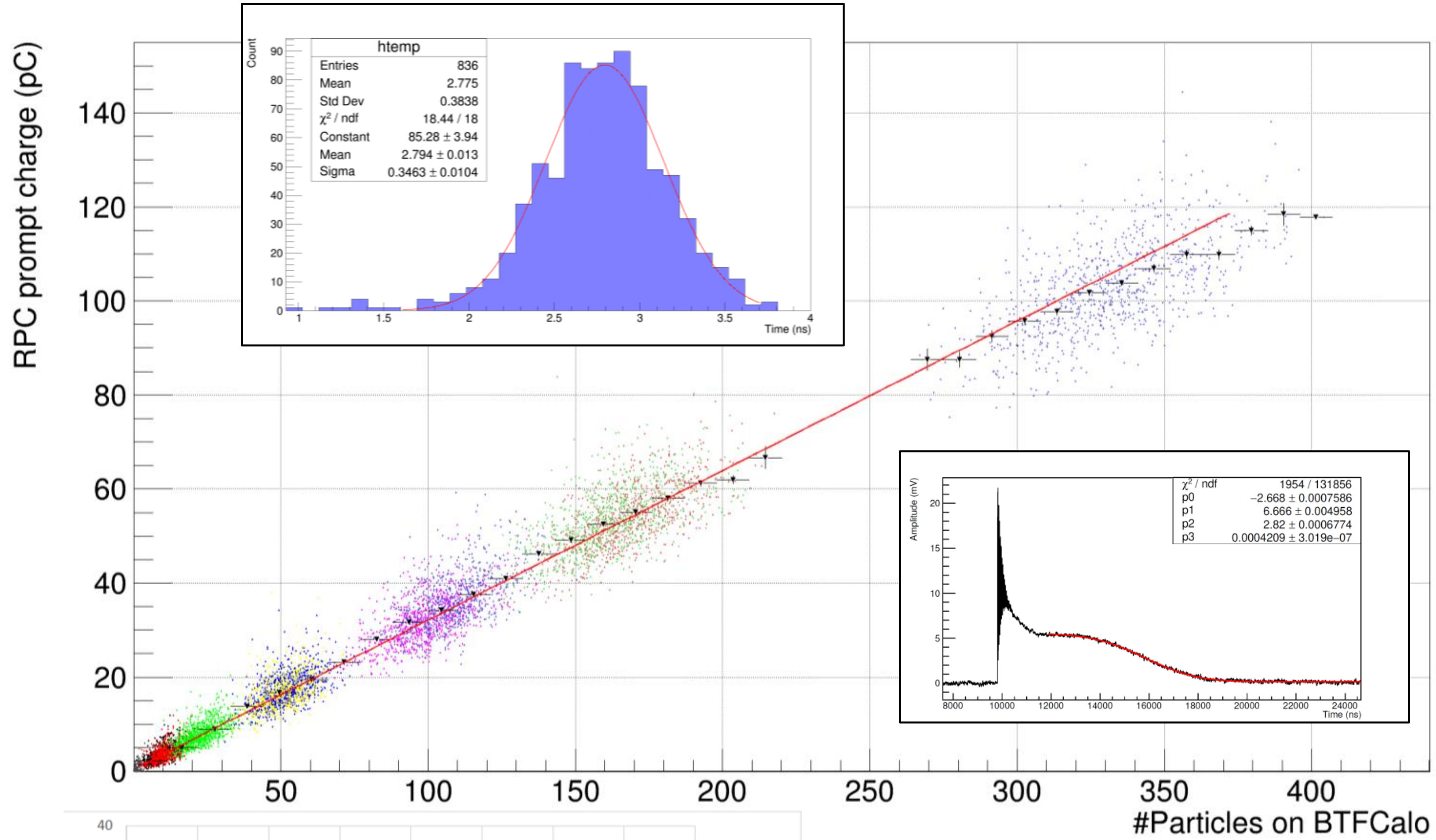
- Lower limit of 40 kHz/cm^2 in rate capability (4 times better then HPL single gap RPC)
- Negligible random counting rate: fraction of 1Hz/cm^2
- Linearity to bunched particles up to 2x10^3 particles/cm^2 (8 particles/cm^2 for 2 mm HPL-RPC operated in streamer mode)

-> To define whether the detector can be used in a real experimental setup, it is necessary to investigate the aging of the material.

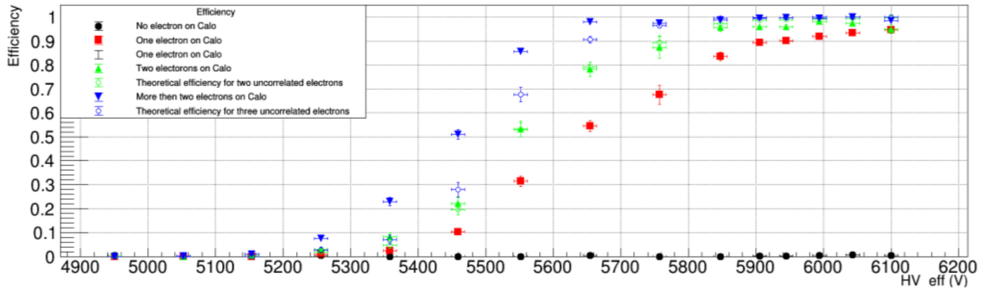
-> Further studies are needed to optimize electrode metallization in order to maximize charge collection without loss of acceptance and time response.

-> Further development of the FE electronics will make it possible to lower the HV working point by making a detector stable which until a few decades ago incurs in destructive discharges.

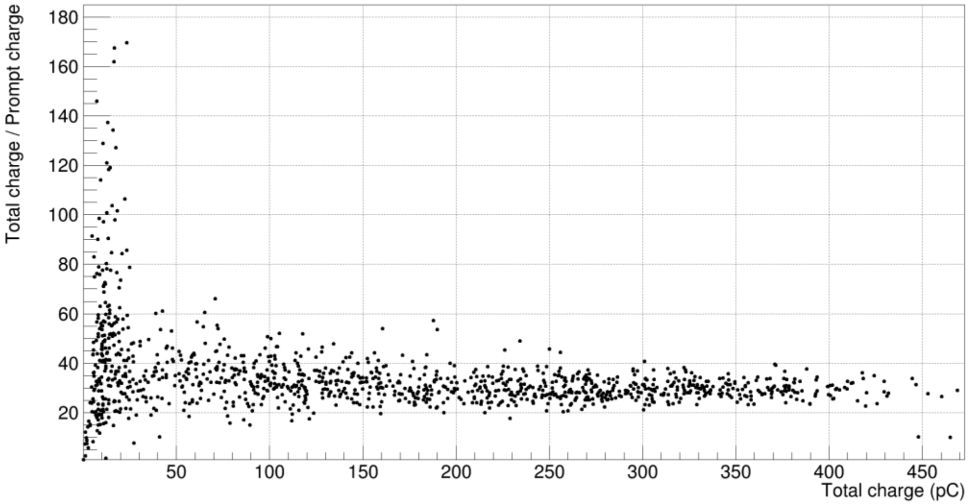
Thanks for the attention



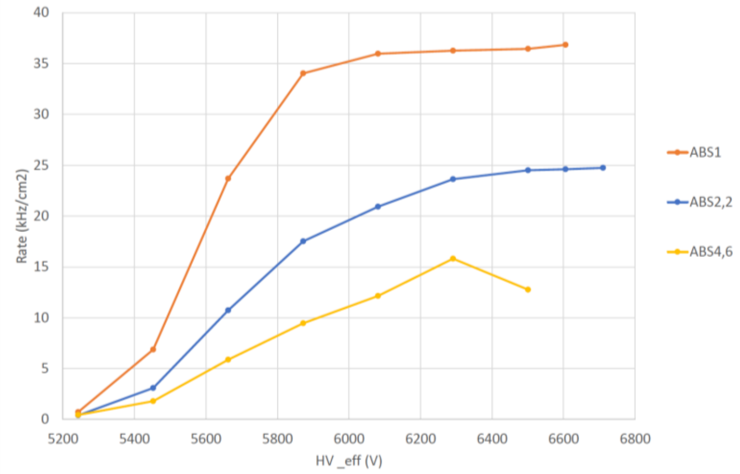
RPC prompt charge (pC)
#Particles on BTFCalo
0
20
40
60
80
100
120
140
50
100
150
200
250
300
350
400
htemp
Entries 836
Mean 2.775
Std Dev 0.3838
χ² / ndf 18.44 / 18
Constant 85.28 ± 3.94
Mean 2.794 ± 0.013
Sigma 0.3463 ± 0.0104
Count
Time (ns)
χ² / ndf 1954 / 131856
p0 −2.668 ± 0.0007586
p1 6.666 ± 0.004958
p2 2.82 ± 0.0006774
p3 0.0004209 ± 3.019e−07
Amplitude (mV)
Time (ns)



Efficiency
No electron on Calo
One electron on Calo
One electron on Calo
Two electorons on Calo
Theoretical efficiency for two uncorrelated electrons
More then two electrons on Calo
Theoretical efficiency for three uncorrelated electrons
HV eff (V)



Total charge / Prompt charge
Total charge (pC)



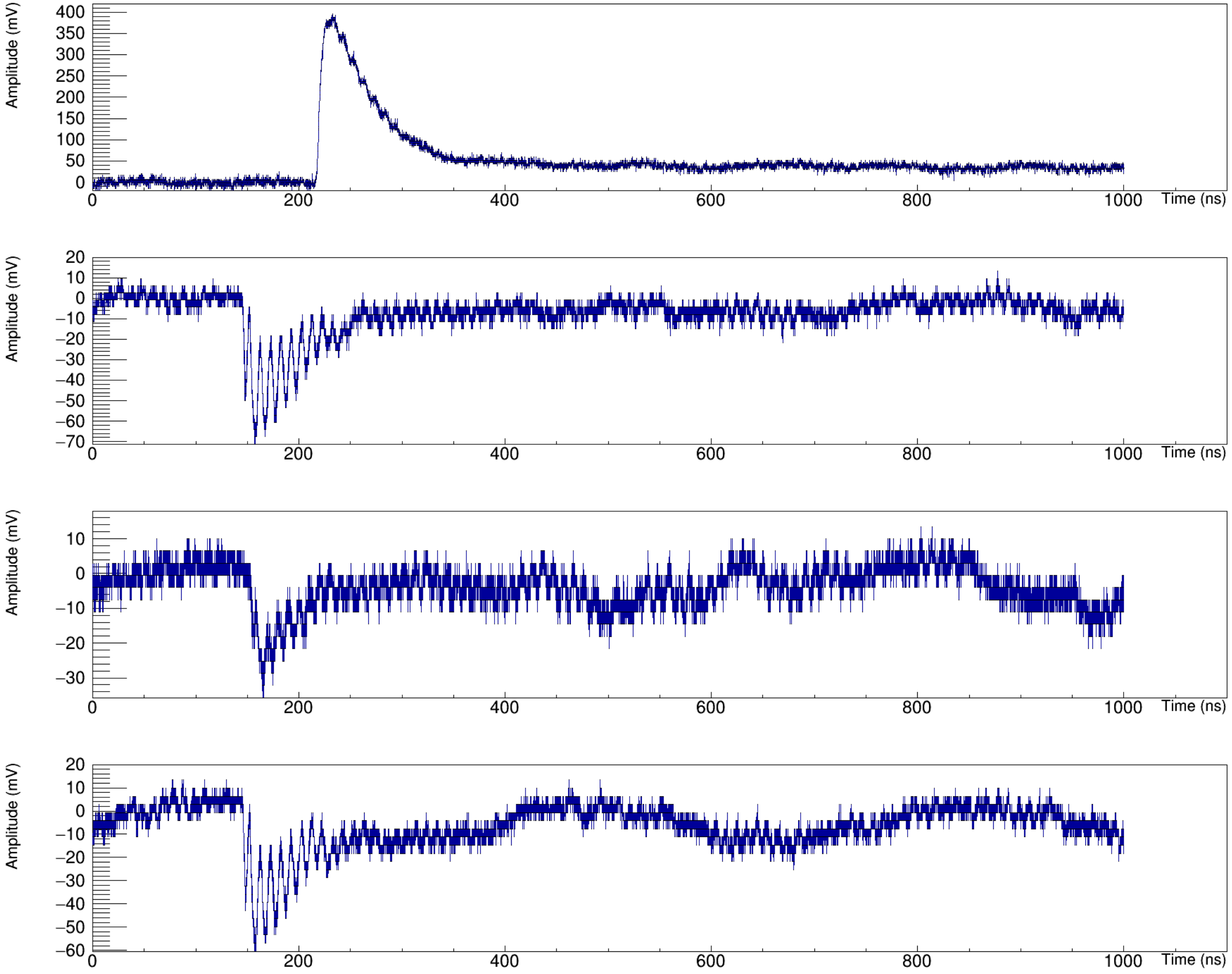
Rate (kHz/cm2)
HV _eff (V)
ABS1
ABS2,2
ABS4,6

Summary

GaAs properties

property	diamond	silicon	Ge	GaAs	4H-SiC
band gap $[eV]$	5.48	1.12	0.67	1.43	3.26
dielectric strength $[V/cm]$	10^{7*}	3×10^5	10^5	4×10^5	5×10^6
intrinsic resistivity $[\Omega/cm]$	$>> 10^{11}$	2.3×10^5	50	10^7	$> 10^5$
electron mobility $[cm^2/Vs]$	$1900 - 4500^*$	1350	3900	8000	1000
hole mobility $[cm^2/Vs]$	$1800 - 3500^*$	480	1900	400	115
electron lifetime [s]	$10^{-10} - 10^{-6*}$	$> 10^{-3}$	$> 10^{-3}$	10^{-8}	5×10^{-7}
hole lifetime [s]	$10^{-10} - 10^{-6*}$	10^{-3}	2×10^{-3}	10^{-7}	7×10^{-7}
saturation velocity $[cm/s]$	$1.2 - 2.7 \times 10^{7*}$	1×10^7	6×10^6	$2 - 1 \times 10^7$ [a]	3.3×10^6
density $[g/cm^3]$	3.52	2.33	5.33	5.32	3.21
average atomic number	6	14	32	31.5	10
dielectric constant	5.72	11.9	16	12.8	9.7
displacement energy $[eV]$	43	$13 - 20$	28	10	$20 - 35$
thermal conductivity $[Wm^{-1}K^{-1}]$	2000	150	60.2	55	120
energy to create e-h $[eV]$	$11.6 - 16^*$	3.62	2.96	4.2	7.8
radiation length, X_0 $[cm]$	12.2	9.36	2.3	2.3	8.7
Energy loss for MIPs $[MeV/cm]$	4.69	3.21	7.36	5.6	4.32
Aver. Signal Created / 100 μm	3602	8892	24860	13300	5100
e-h pairs/X_0 $(10^6 cm^{-1})$	5.7	10	5.67	2.99	4.5

Induced signal



GaAs characterization