

SI-GaAs wafers as resistive electrode for high-rate RPC with very low dark count rate

XVI Workshop on Resistive Plate Chambers and Related Detectors

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CERN

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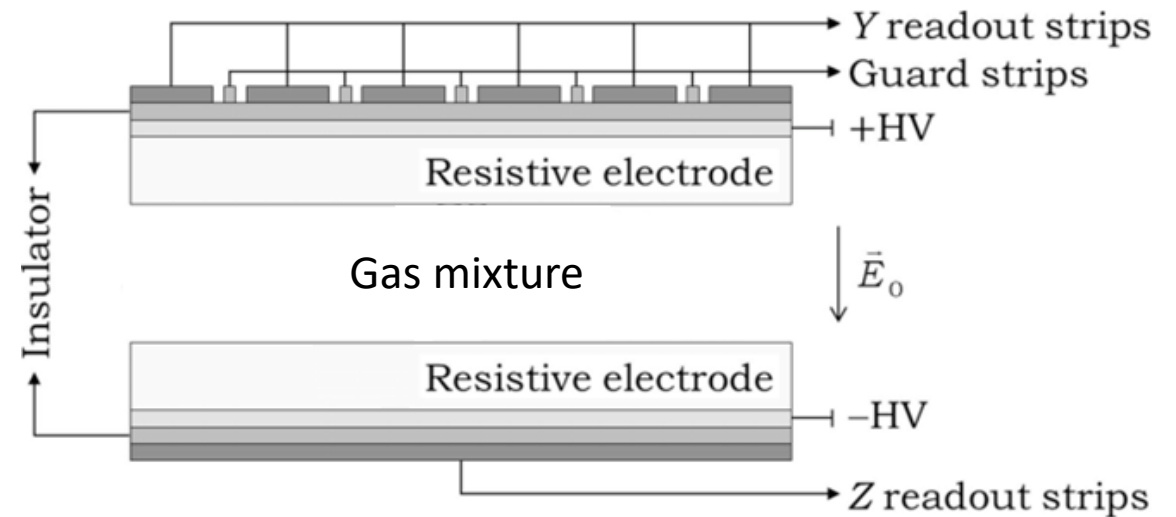


Outline

- 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/cm² (2fC threshold)
- Cost ~ 2 k€/m² (depending on the readout granularity)
- Detector lifetime above 0.3 C/cm²
- Detector thickness ~ 1 cm



PERSPECTIVES AND LIMITING FACTORS

✓ High Rate

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

- The improvements on the FE electronics and detector design shift the intrinsic rate capability up to $\sim 7 \text{ kHz/cm}^2$
- The HPL electrodes guarantee stable operation up to a total integrated charge of 0.3 C/cm^2 --> **Effective rate capability significantly limited by the 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 $10^{10} \Omega\text{cm}$ resistivity

[T. Franke et al. "Potential of RPCs for tracking", NIM Section A, Volume 508]

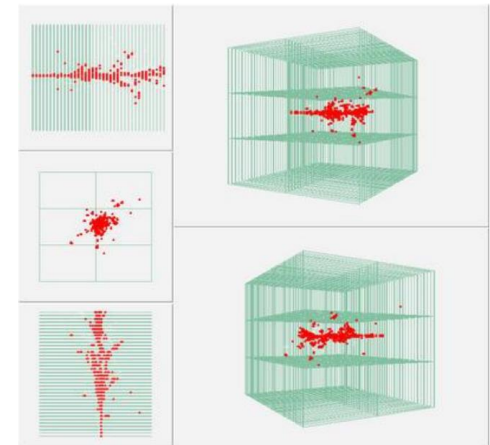
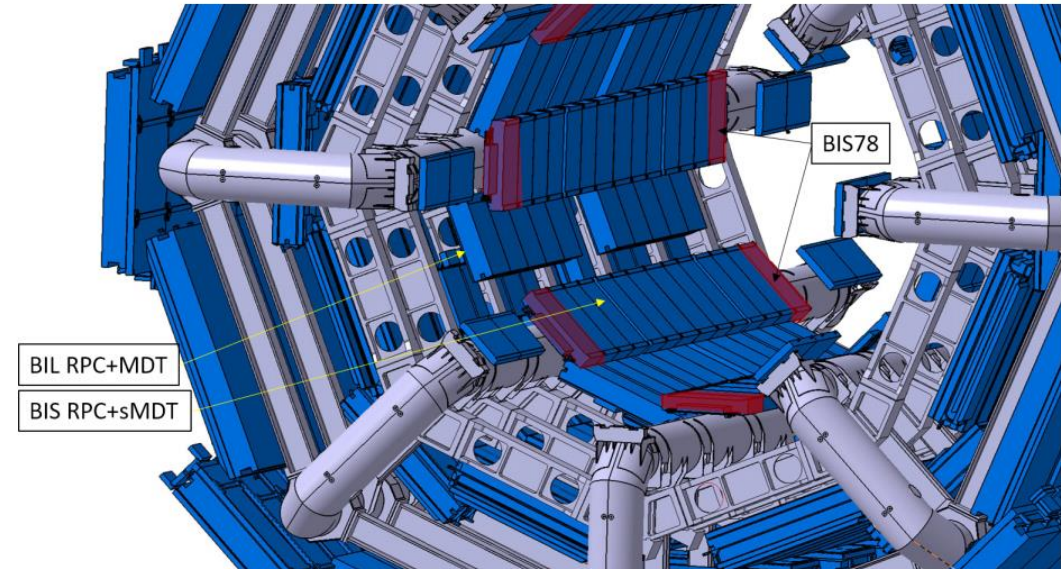
(Semi Insulating Gallium Arsenide Wafers): Low resistivity, Crystal structure, Thin electrode

+

Low noise FE electronics: threshold down to 4-6 fC

✓ Calorimetry

- So far, the intrinsic linearity limit of the RPCs for multiple synchronous particles was measured only in the streamer operating mode.



[J. Repond, On behalf of the CALICE collaboration Recent DHCAL Developments]

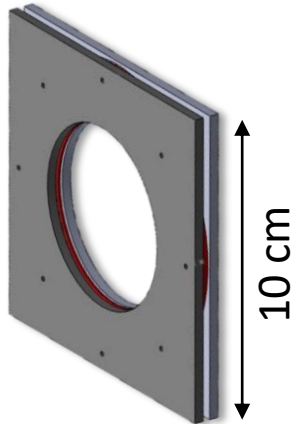
PROTOTYPE DESIGN AND FE-ELECTRONICS

Gas inlet \varnothing 2 mm \rightarrow \varnothing 0.6 mm

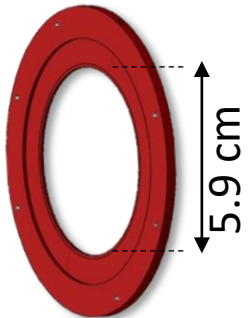
[R. Cardarelli et al, "Performance of RPCs and diamond detectors using a new very fast low noise preamplifier"]



Wafers holder

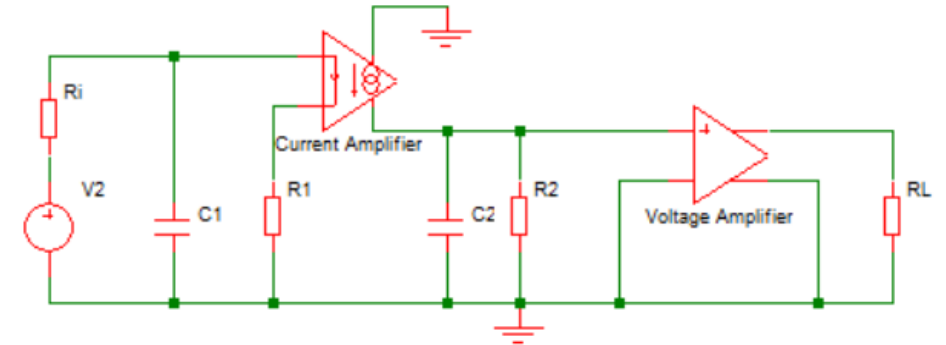


Wafers spacer 1 mm

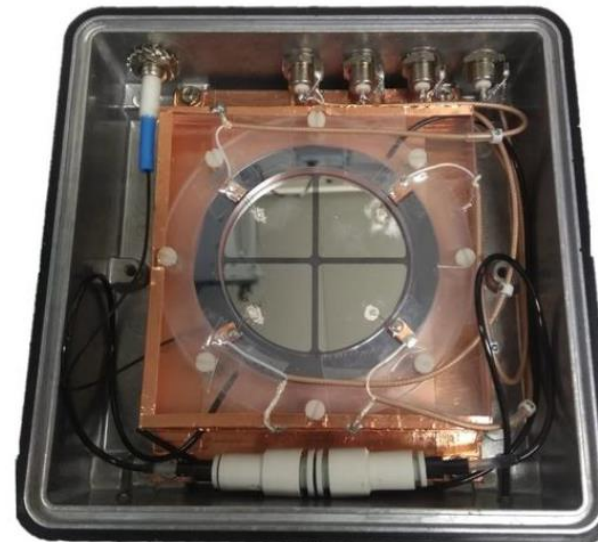


Material	Semi Insulating undoped GaAs
Thickness	640 – 643; μm
Diameter	3"
Resistivity	$1.4 \times 10^8 \Omega cm$
Surface treatment	both polished
Growth method	VGF
Orientation	$(100) \pm 0.01^\circ$
Mobility	$5300 cm^2/Vs$

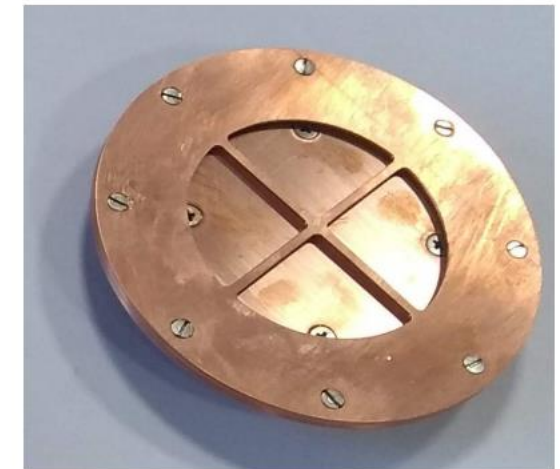
Voltage supply	3–5 Volt
Sensitivity	2–4 mV/fC
Noise (independent from detector)	4000 e^- RMS
Input impedance	100–50 Ohm
B.W.	10–100 MHz
Power consumption	10 mW/ch
Rise time $\delta(t)$ input	300–600 ps
Radiation hardness	1 Mrad, $10^{13} n cm^{-2}$



Thanks to Prof. M. Lucci for the GaAs metallization



Wafers sputtering holder



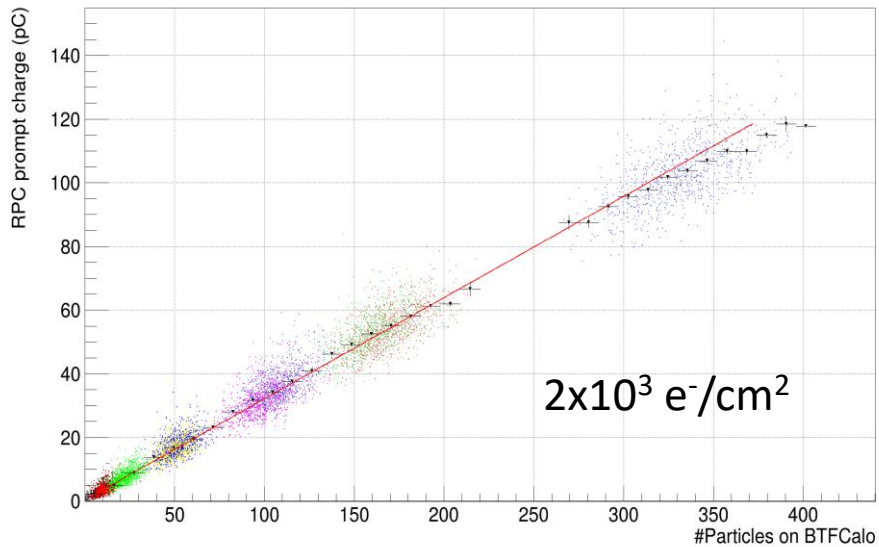
FIRST RESULTS AT THE BEAM TEST FACILITY (2019-2020)

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

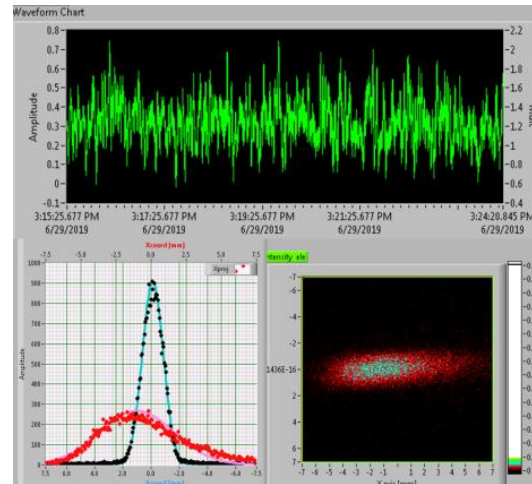
beam properties:

- Gaussian shape,
- $\sim 20\text{Hz}$ bunch frequency
- 250 MeV electrons;
- intensity up to 400 e^-/bunch ;

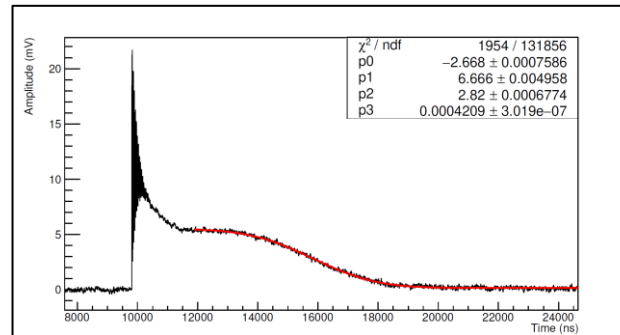
Linearity response in avalanche mode 1 mm gas gap



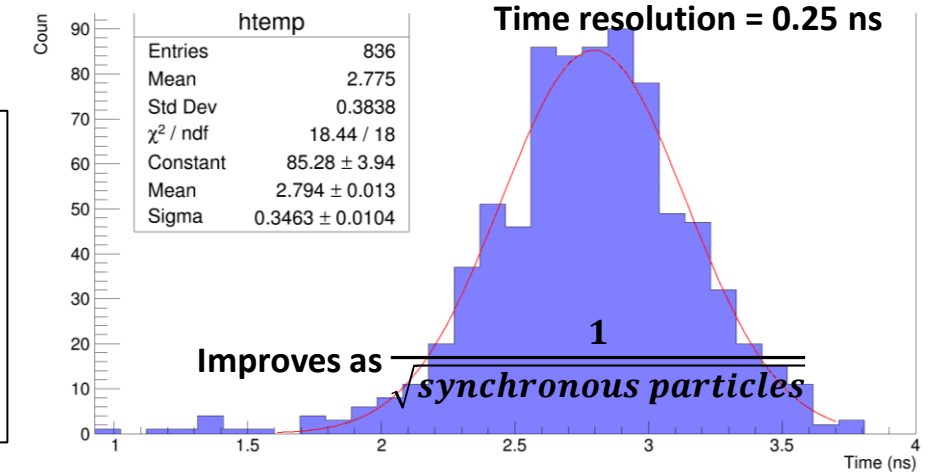
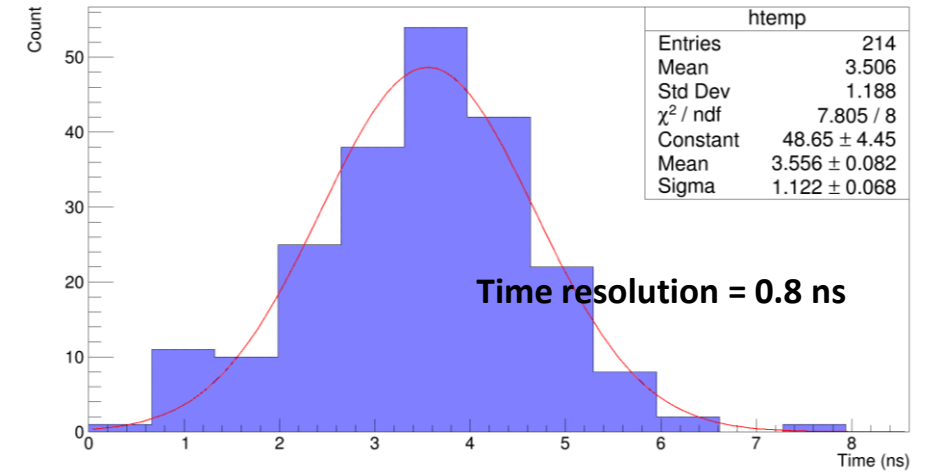
[A. Rocchi et al "Linearity and rate capability measurements of RPC with semi-insulating crystalline electrodes operating in avalanche mode"]



Total signal on 1 k Ω from bunched e^-



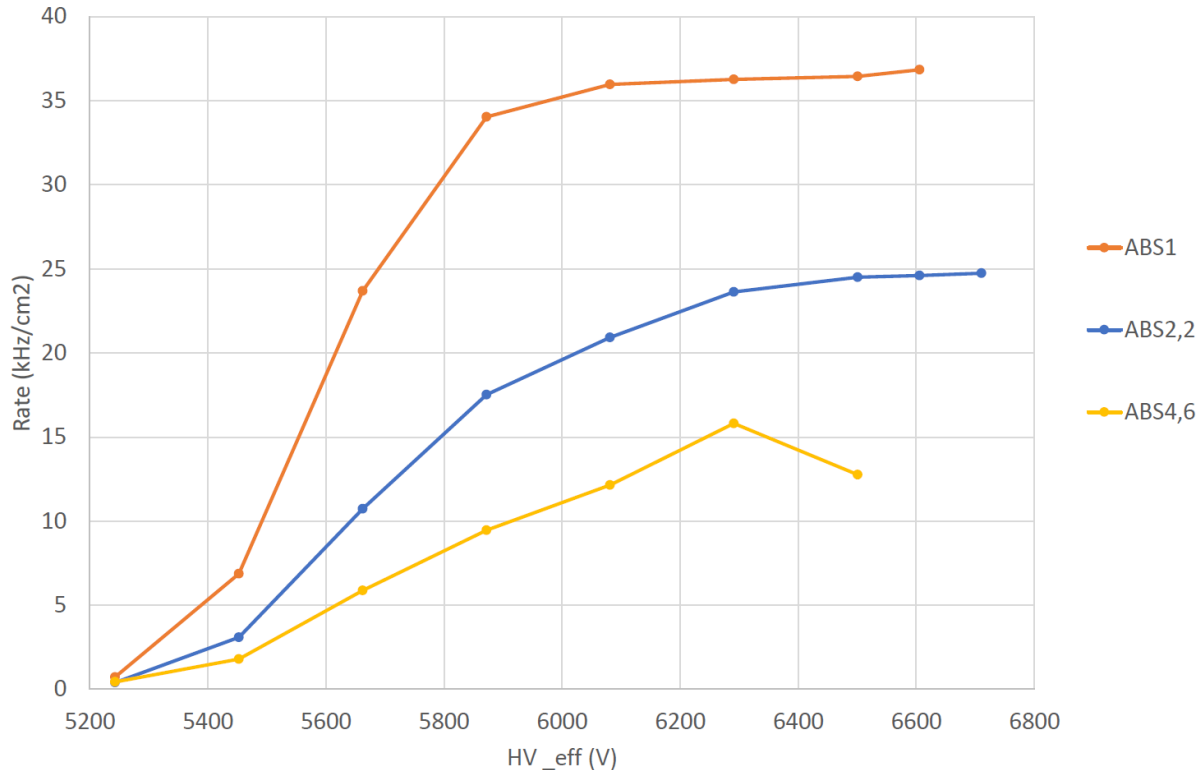
Time resolution with bunched particles



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.



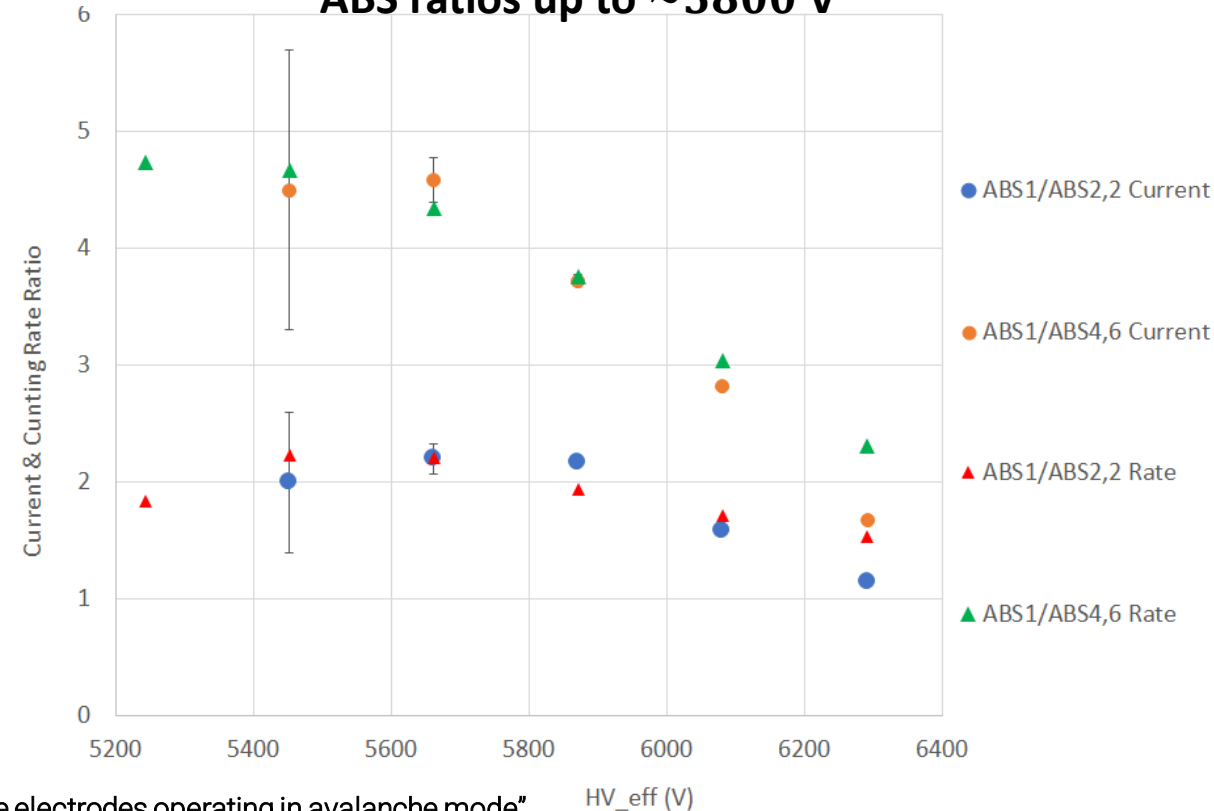
A. Rocchi et al "Linearity and rate capability measurements of RPC with semi-insulating crystalline electrodes operating in avalanche mode"

Expected ratios (without saturation)

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

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

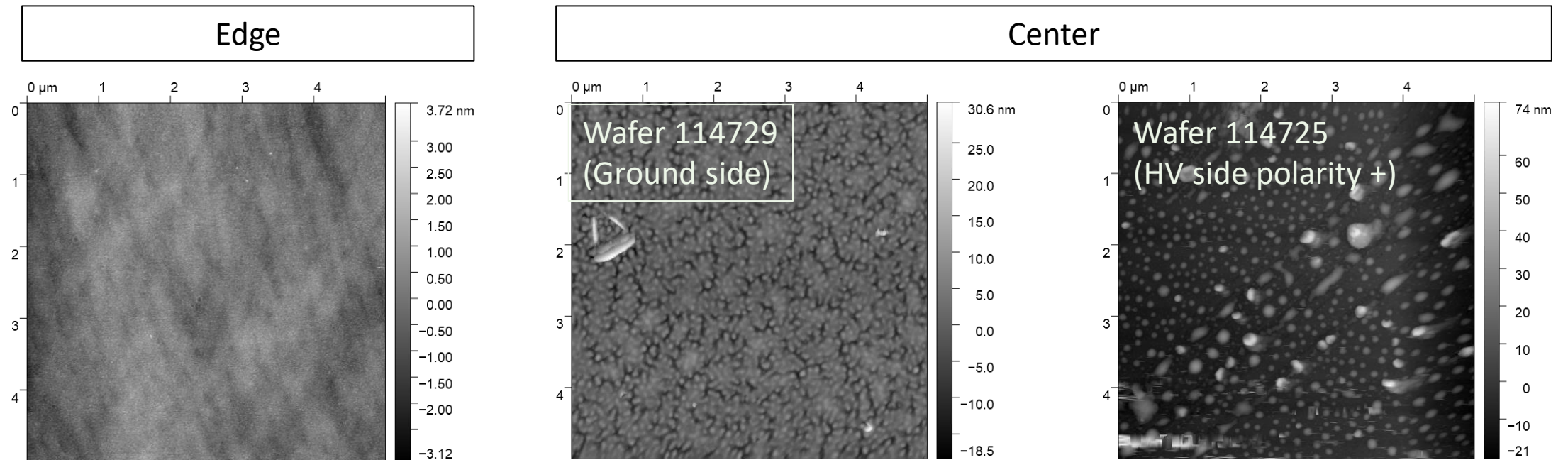
Counting rate and current ratios are consistent with the ABS ratios up to ~5800 V



FIRST AGING OBSERVATION

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

- Microstructures 58-96 nm tall 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



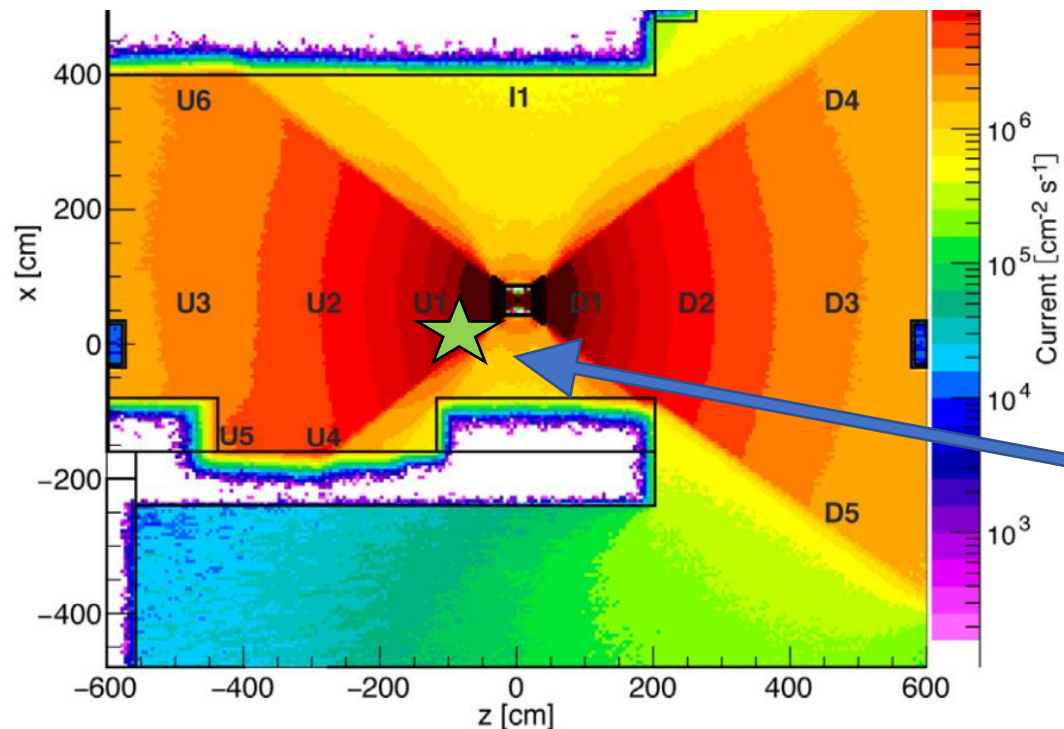
Thanks to Prof. Ernesto Placidi

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 (2021-ONGOING)

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

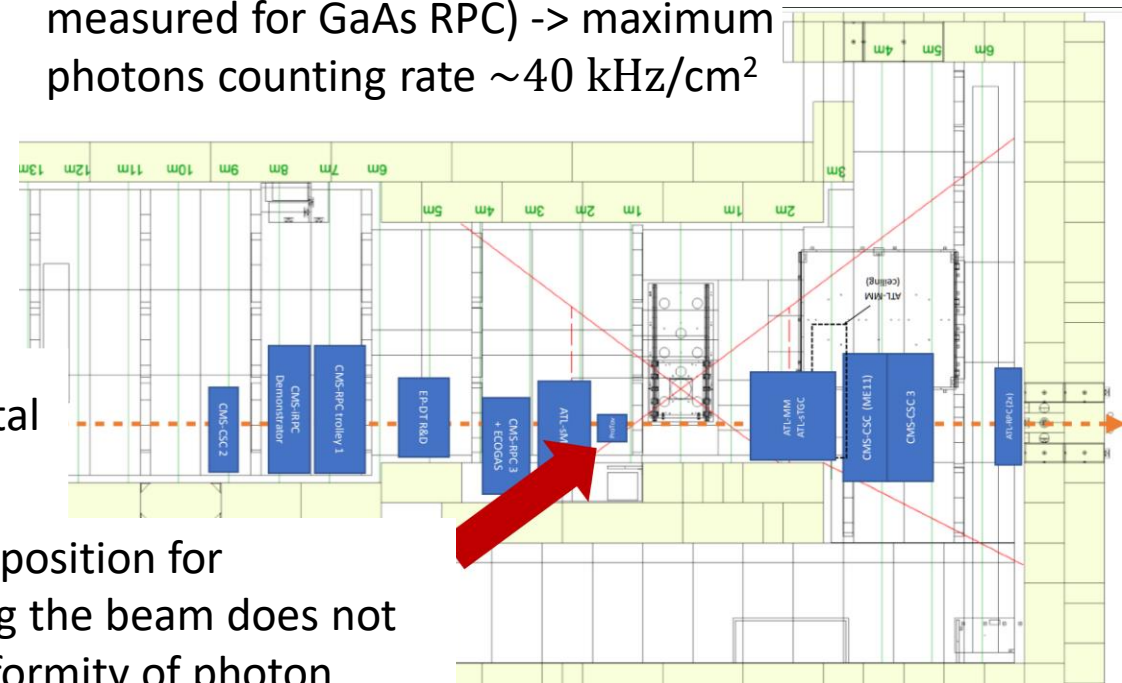
- 14.9 TBq ^{137}Cs source (662 keV photons 33% - 54%)
- Constant photon current in the xy plane for 662 keV photons
- 180 GeV/c muons beam



The setup was placed in the upstream **region U1**
 -> **Maximum photon current $4.3 \times 10^7 \frac{\text{photons}}{\text{cm}^2 \text{s}}$**
No photon converter on the electrode surface
 -> RPC photon efficiency $\sim 10^{-3}$ (to be measured for GaAs RPC) -> maximum photons counting rate $\sim 40 \text{ kHz/cm}^2$

Experimental setup

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

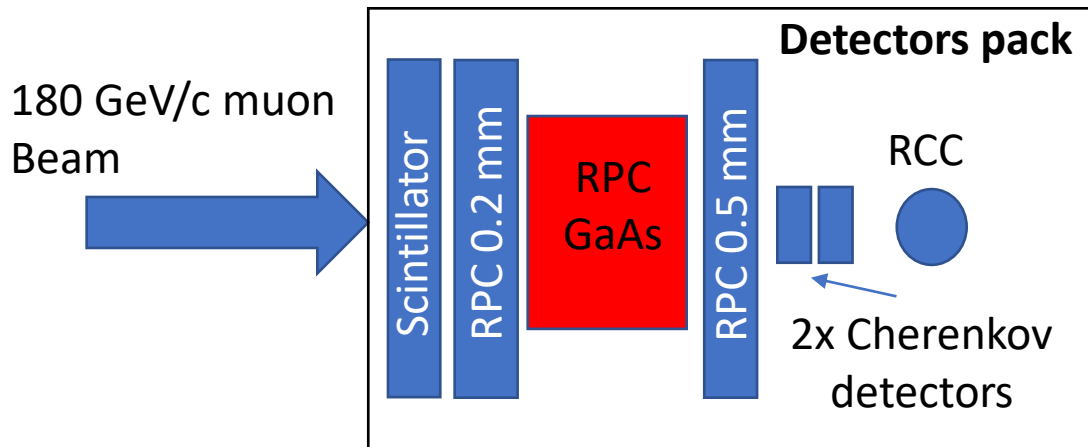


EXPERIMENTAL SETUP

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

Dual timer pulse generator

Beam line scintillators

1 x Cherenkov Detector

Caen 1742 32ch digitizer
12 bit 5 GS/s, set to 200 ns Time window

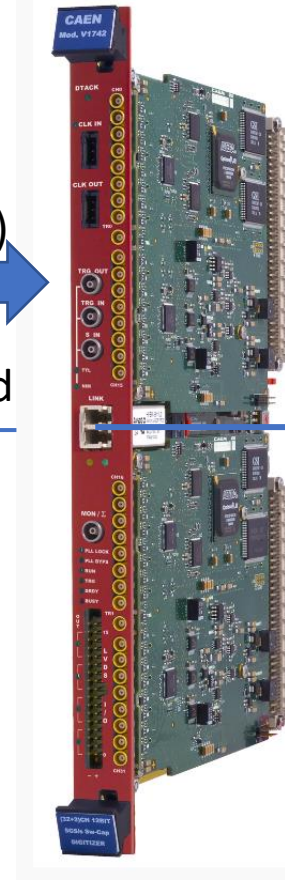
Signal cables
(5 m (H8)/25 m Gif++)

Fast Trigger and acquisition

Wdt 60 ns

OR

Wdt 20 ns



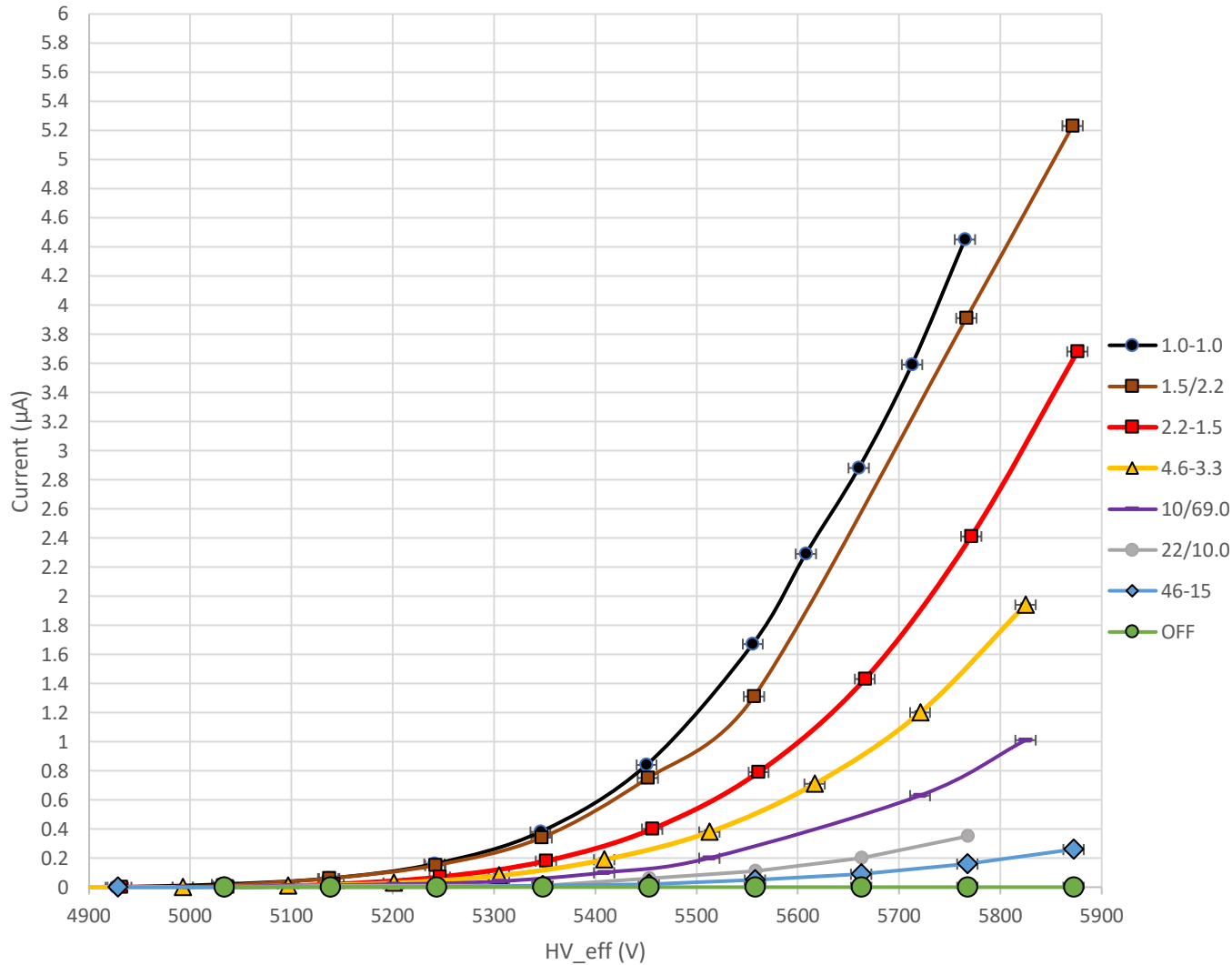
Optical Link

USB link



Caen 3818

CURRENTS VS ATTENUATION

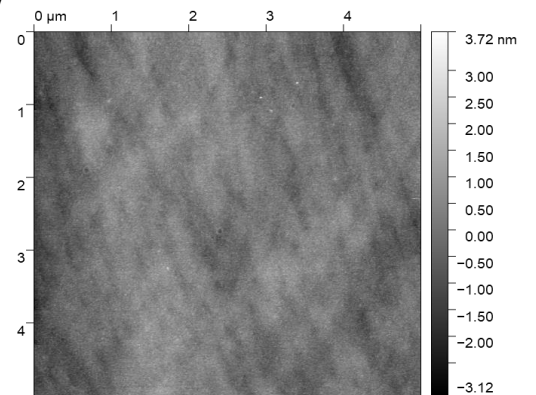


The first point that stands out when observing the current absorbed by the detector, is the absence of ohmic component and the negligible random counting rate

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

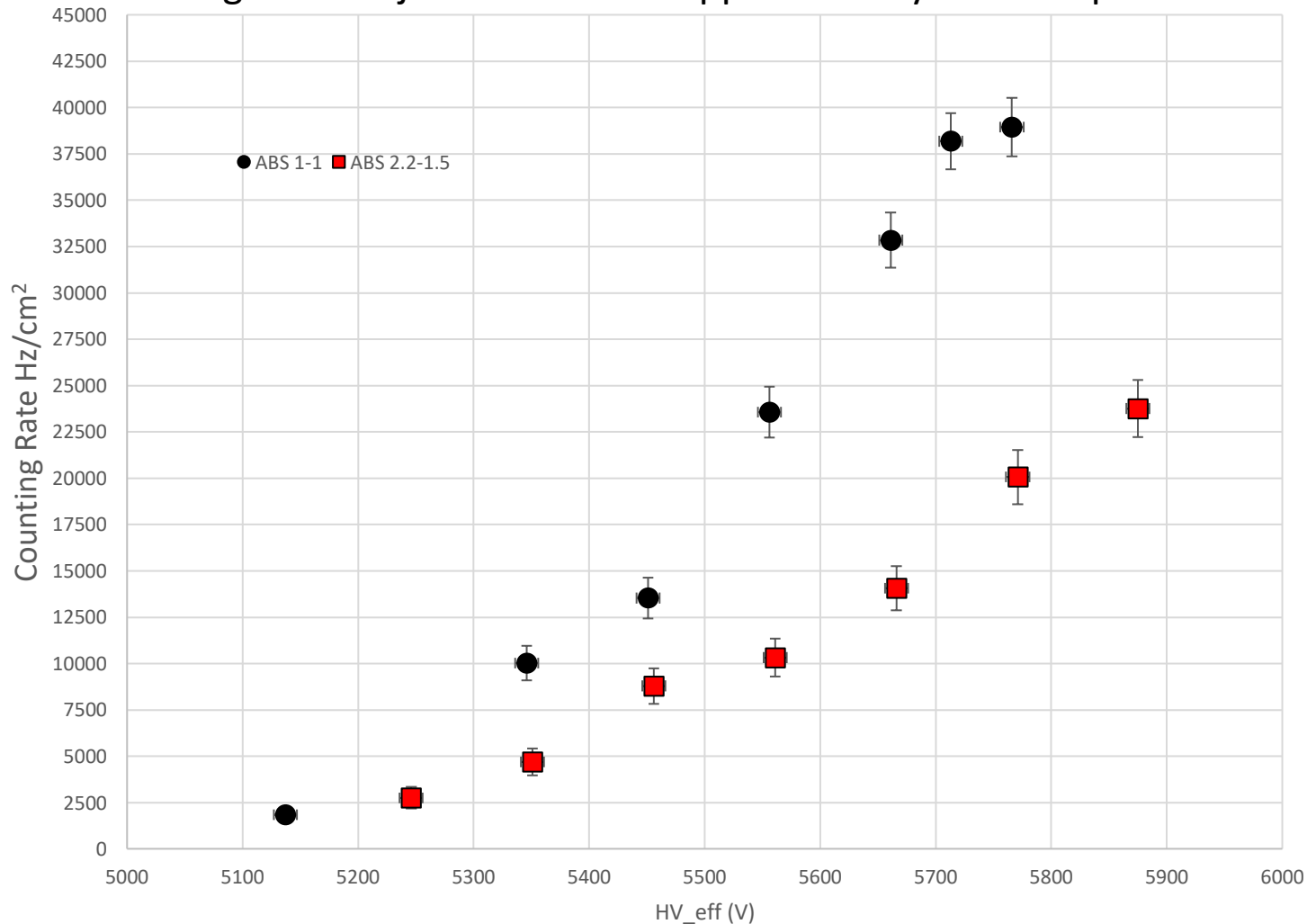
Also with photon background, the current is not measurable with the experimental sensitivity for voltage lower then 5000 V

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 rejection factor is approximately 10^3 as expected

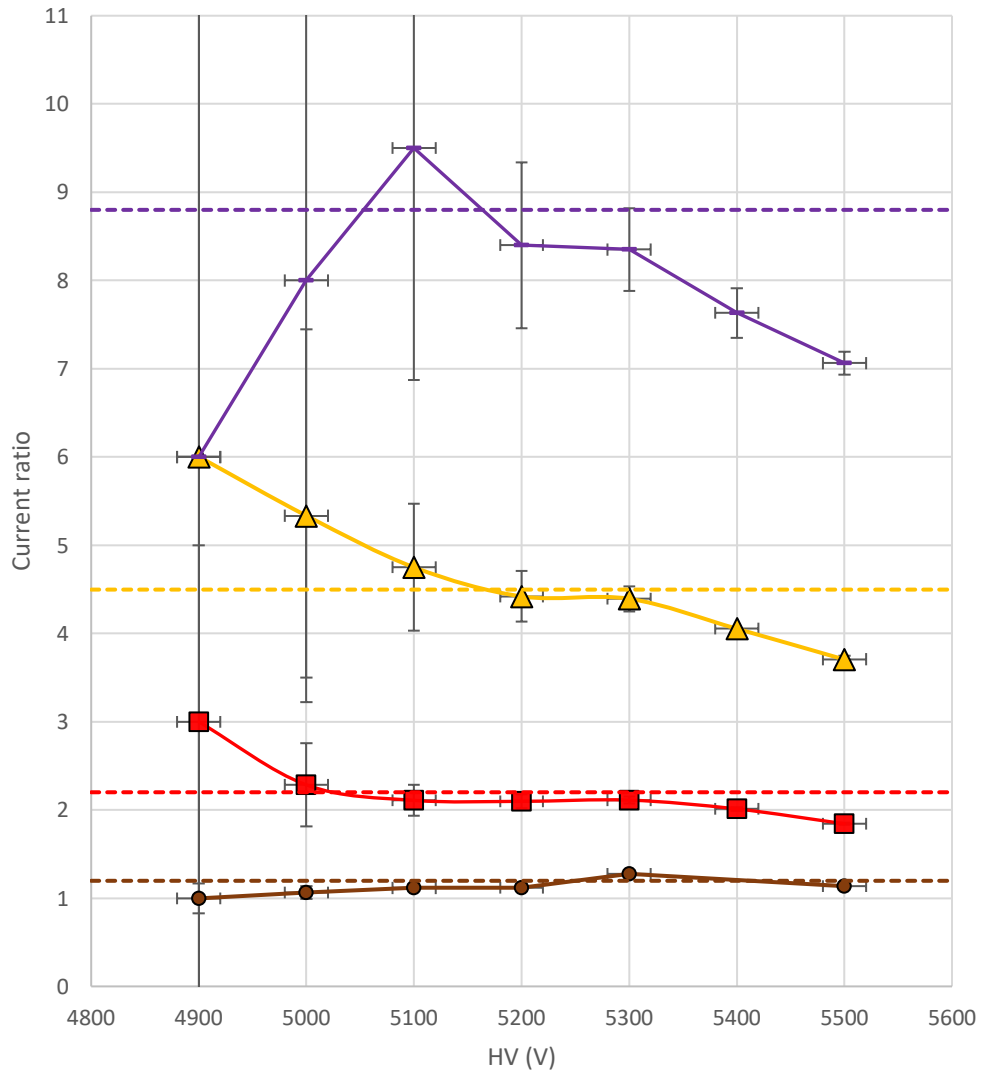


The counting rate has been measured acquiring random counts out of spills. Each time window is 200 ns so about 3000 events have been integrated for each HV working point.

The maximum counting rate measured is about 39 kHz/cm² in a 4.3×10^7 photons/cm²s radiation field ,

consistent with that measured with the old prototype in the DownStream position (36 kHz/cm²) at almost same distance from the source. In that case the signals were just discriminated and counted

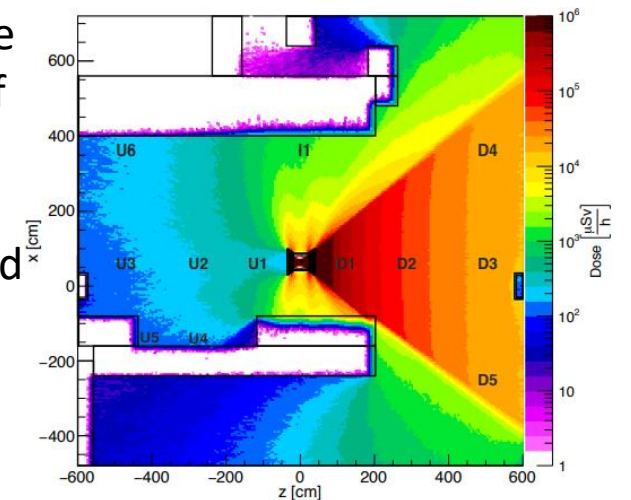
ATTENUATION FACTORS MEASUREMENTS



Attenuation of 662 keV gammas	Measured attenuation		
	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.

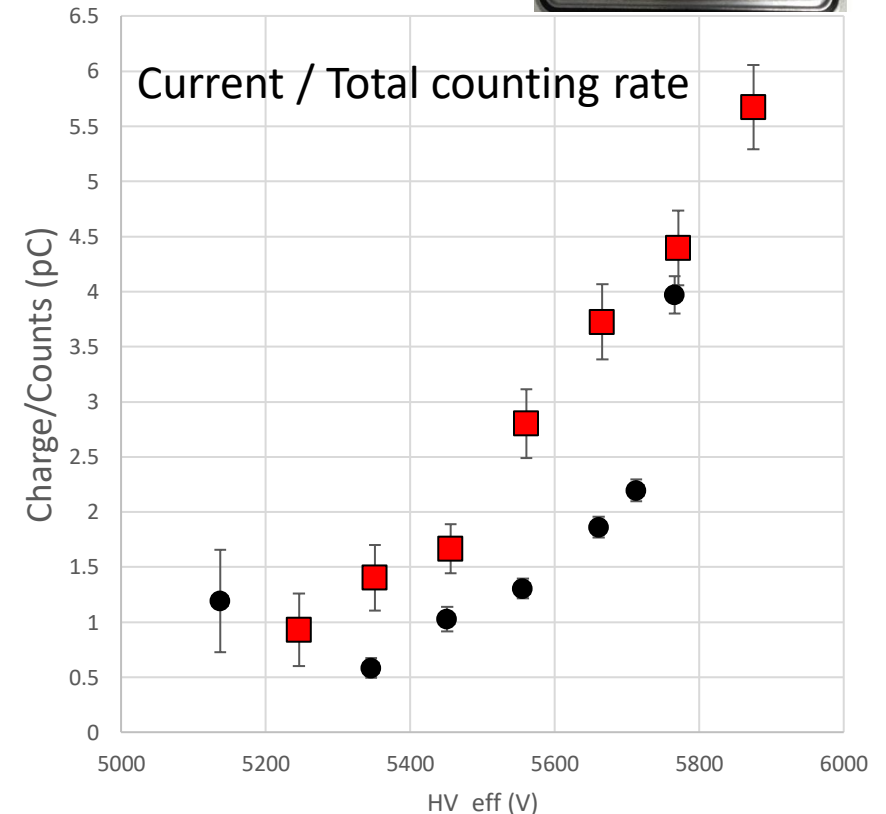
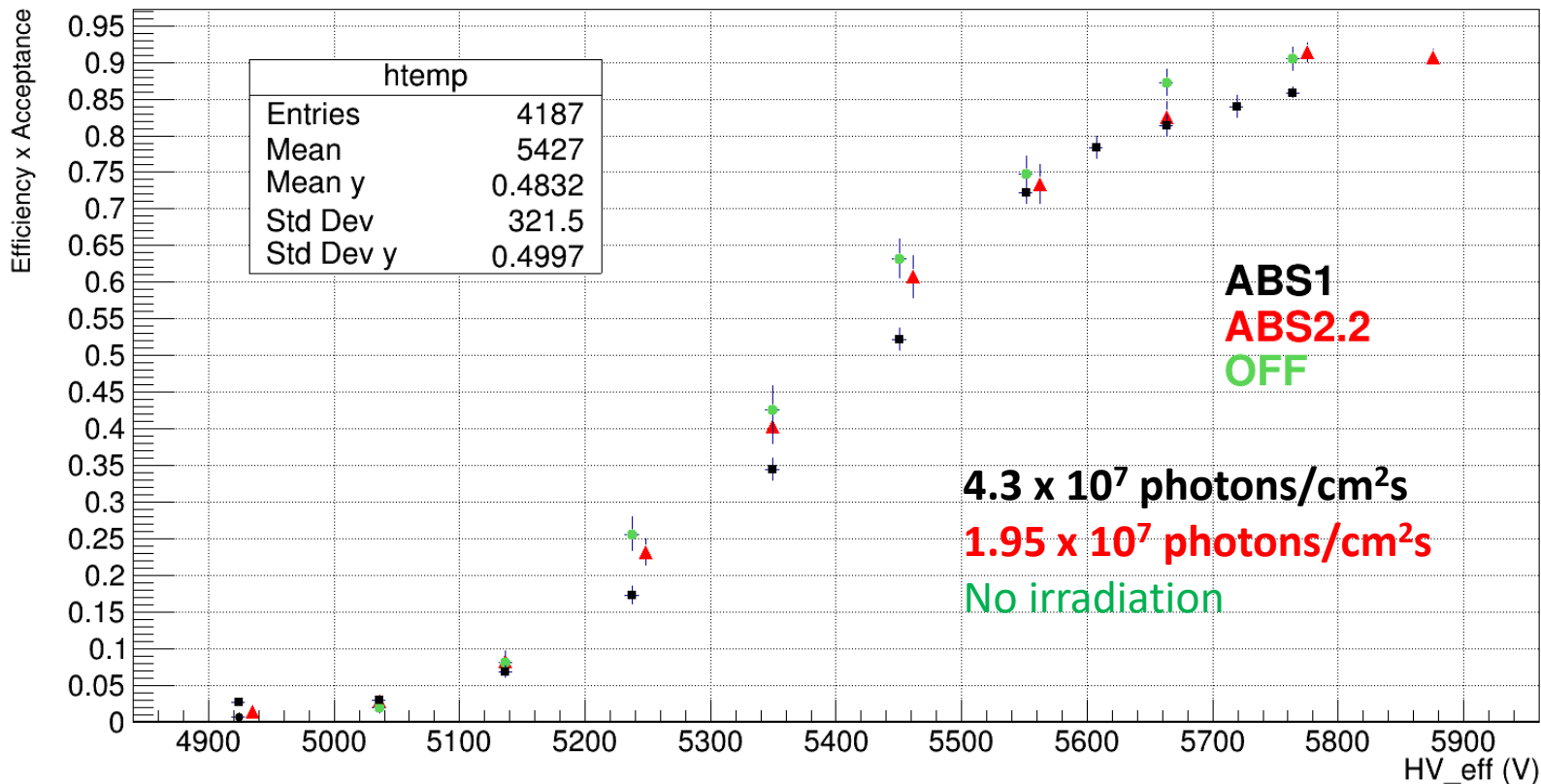
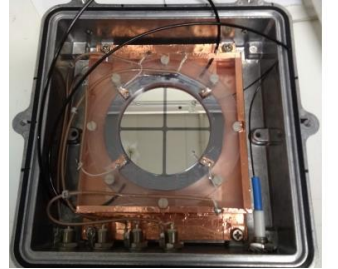
The attenuation factors of the source have been measured by the ratios of the currents and are consistent with the reference values up to the knee of efficiency. It should be emphasized that the reference values only take into account the 662 keV ranges and some crosstalk between US and DS rise up in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

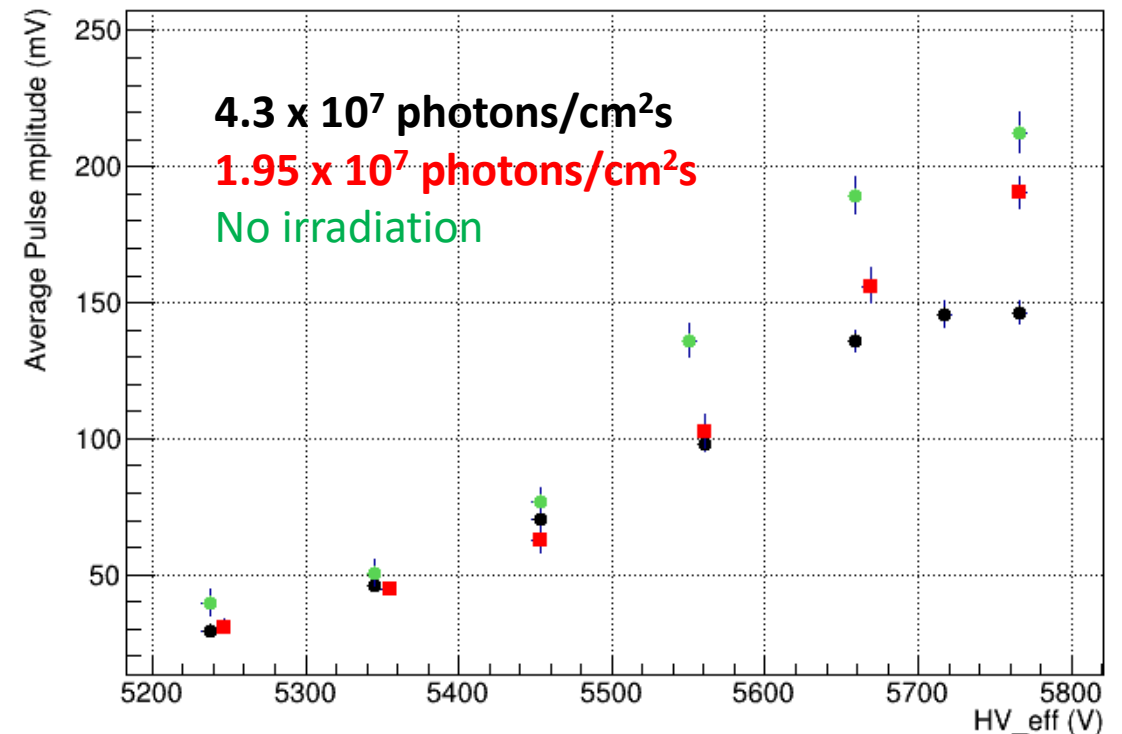
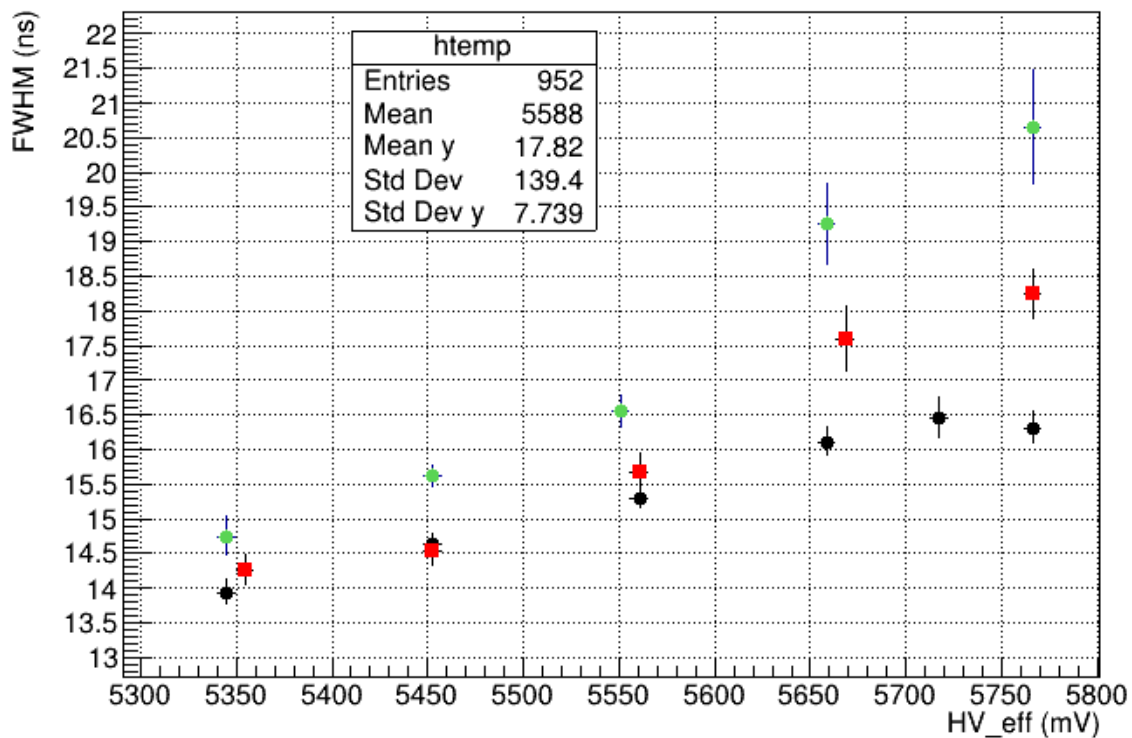


PULSE SHAPE PARAMETERS

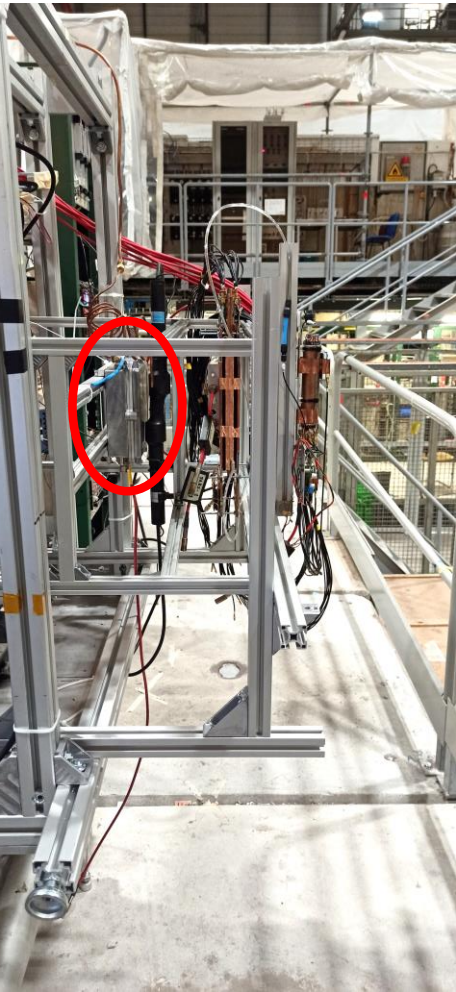
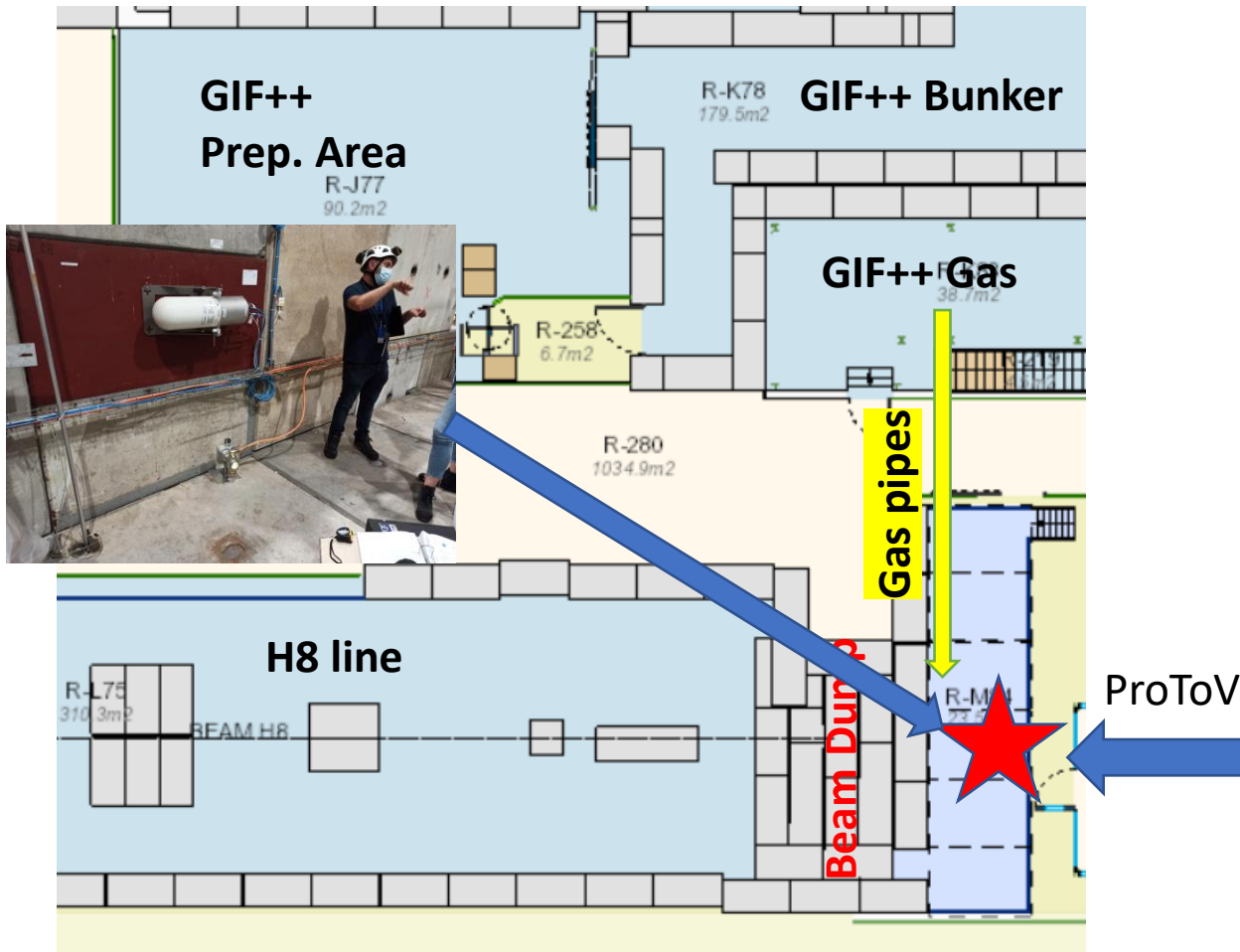
Despite the small impact on the efficiency performance, the signal attenuation with high photon irradiation is clearly visible from the signal parameters.

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.



NEW SETUP @ H8 BEAM DUMP PLATFORM (2021-ONGOING)



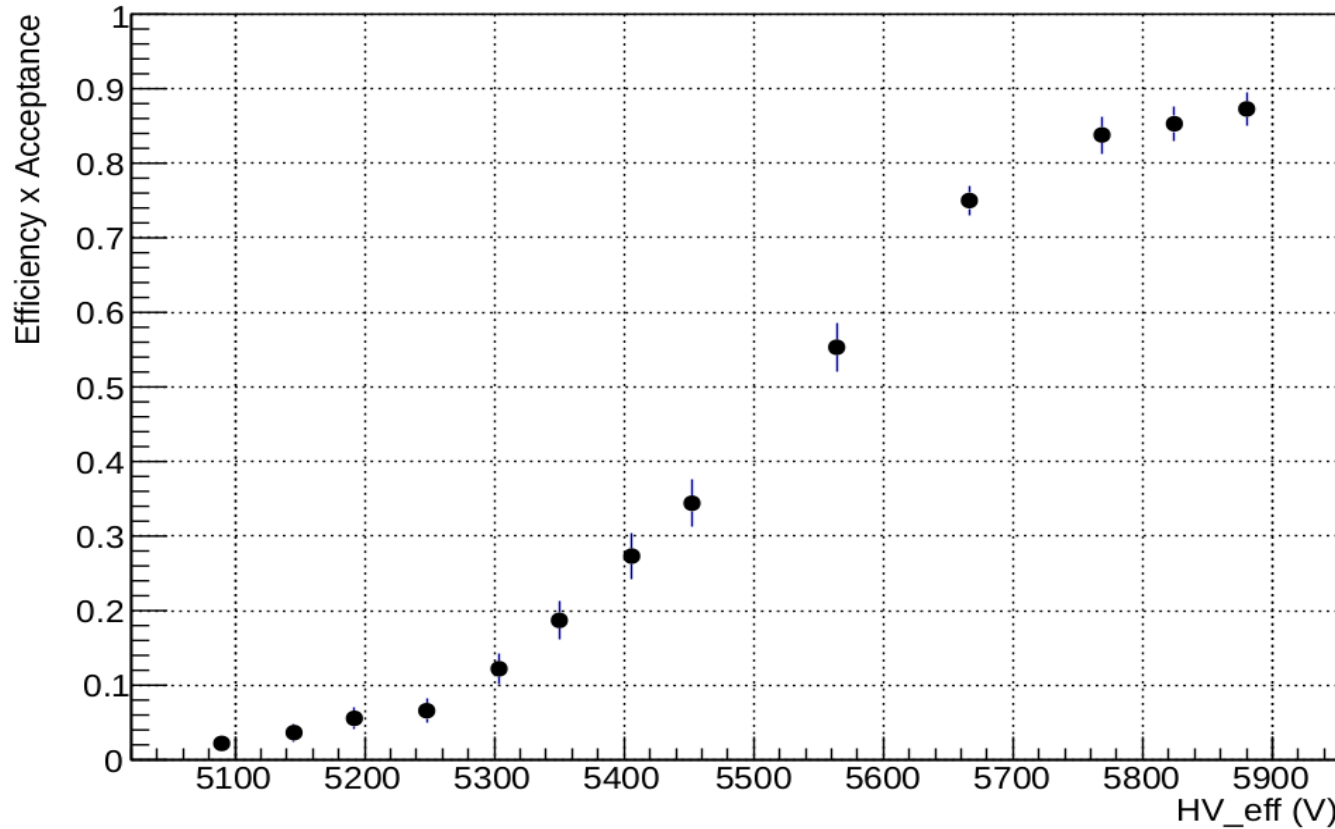
2 gas pipes shared with CMS-RPC

- Wet Standard mixture
- Dry Standard mixture

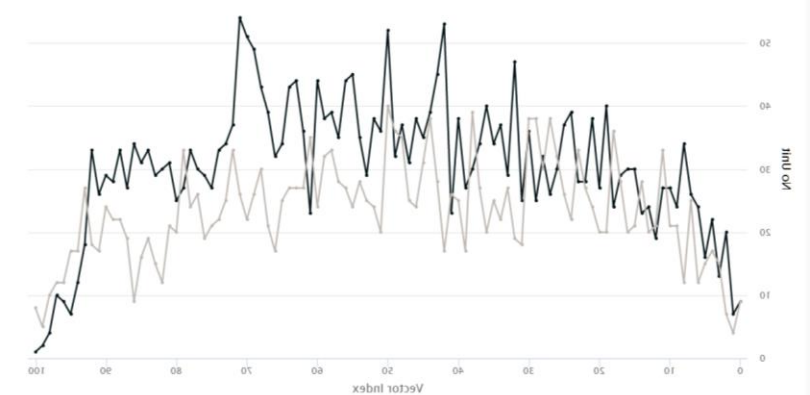


NEW SETUP @ H8 BEAM DUMP PLATFORM

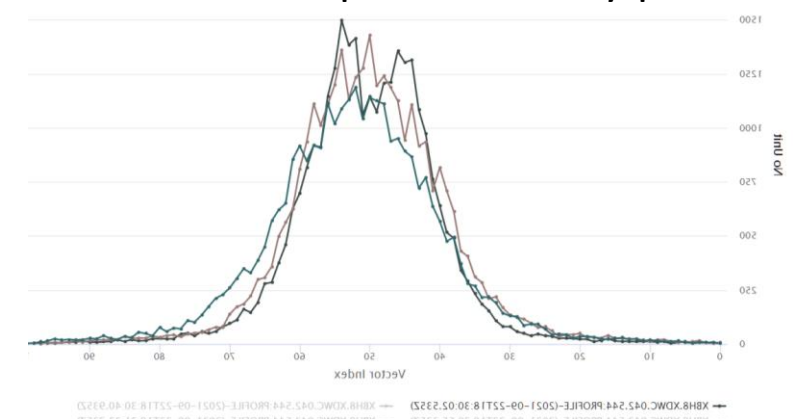
Even the preliminary test on the H8 line shows an acceptance limit, probably due to the layout of the readout pick-up / HV electrode. The beam profile is still larger as respect to the tested prototypes -> we are working on new trigger detectors for medium size



Two beams possibility in this position:



Residual from dumped secondary pions beam



tertiary muon beam

About 8 cm FWHM before the dump

Conclusions

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

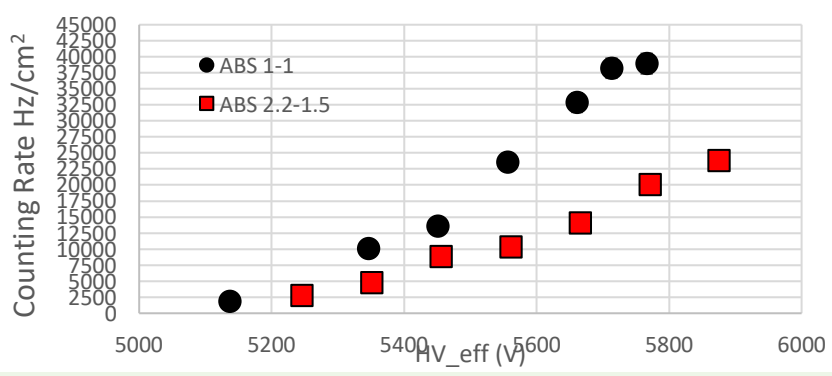
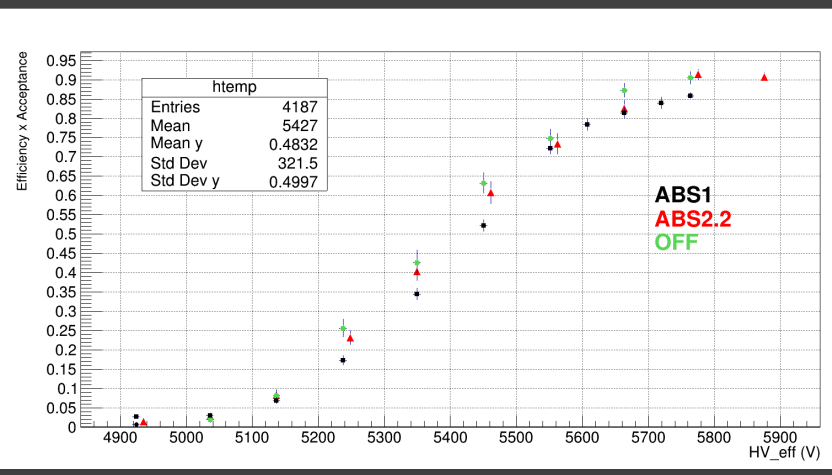
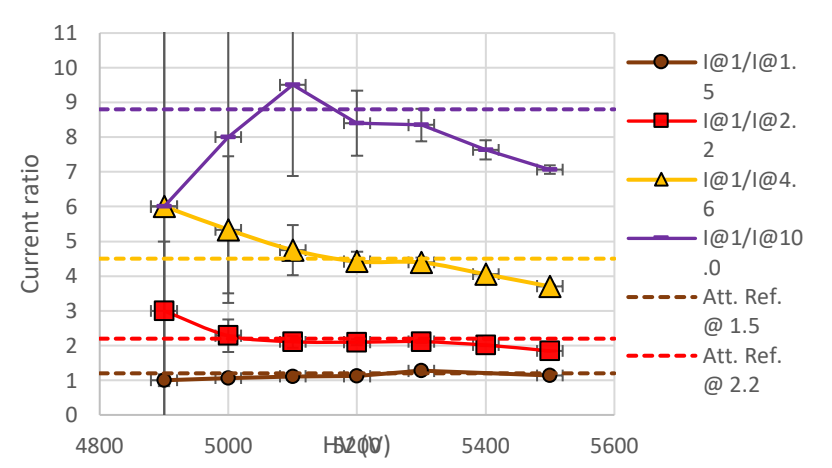
- Rate capability up to 40 kHz/cm²
- Negligible random counting rate
- About 10³ gamma rejection
- Linearity to bunched particles up to 2x10³ particles/cm²

All these results have finally been demonstrated by acquiring the analog signals and studying their characteristics

-> To define whether the detector can be used in a real experimental setup, it is necessary to investigate the problem of aging. This test will be performed next year at the Gif++ facility. A first test will be performed in the next days to check if the random counting rate are still negligible after several month of operation.

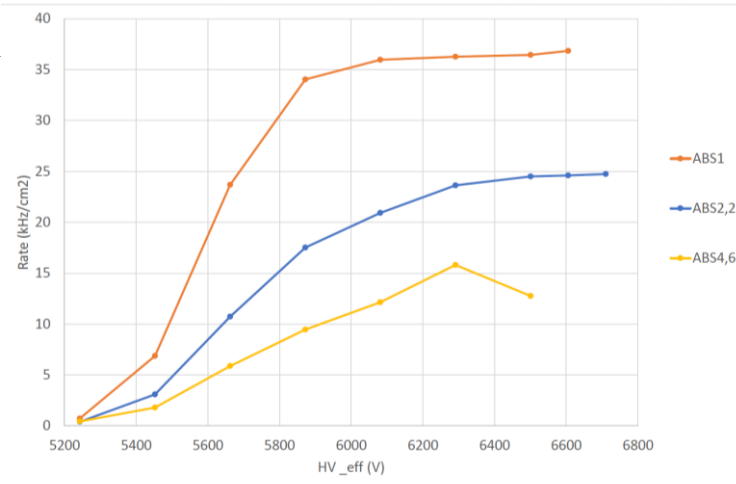
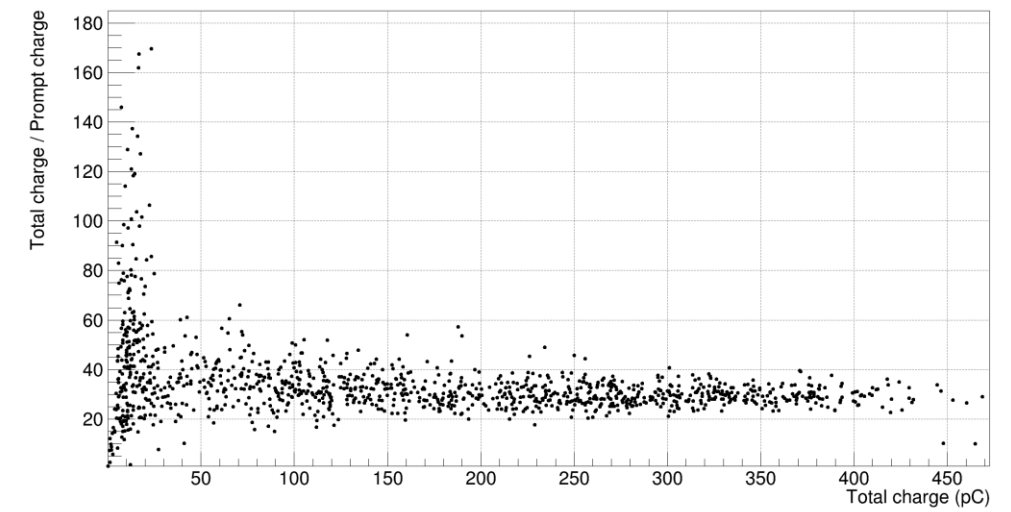
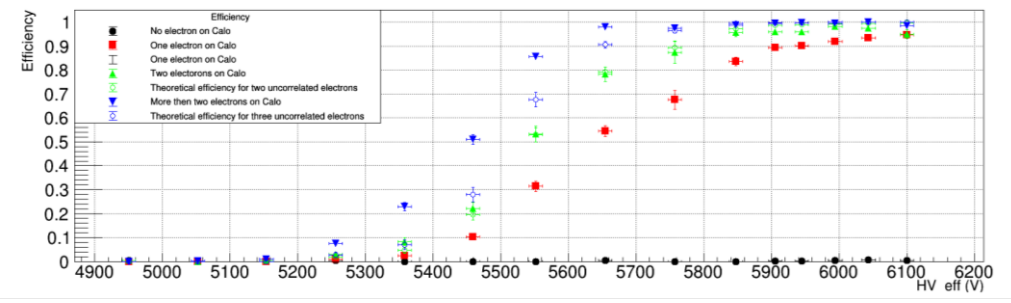
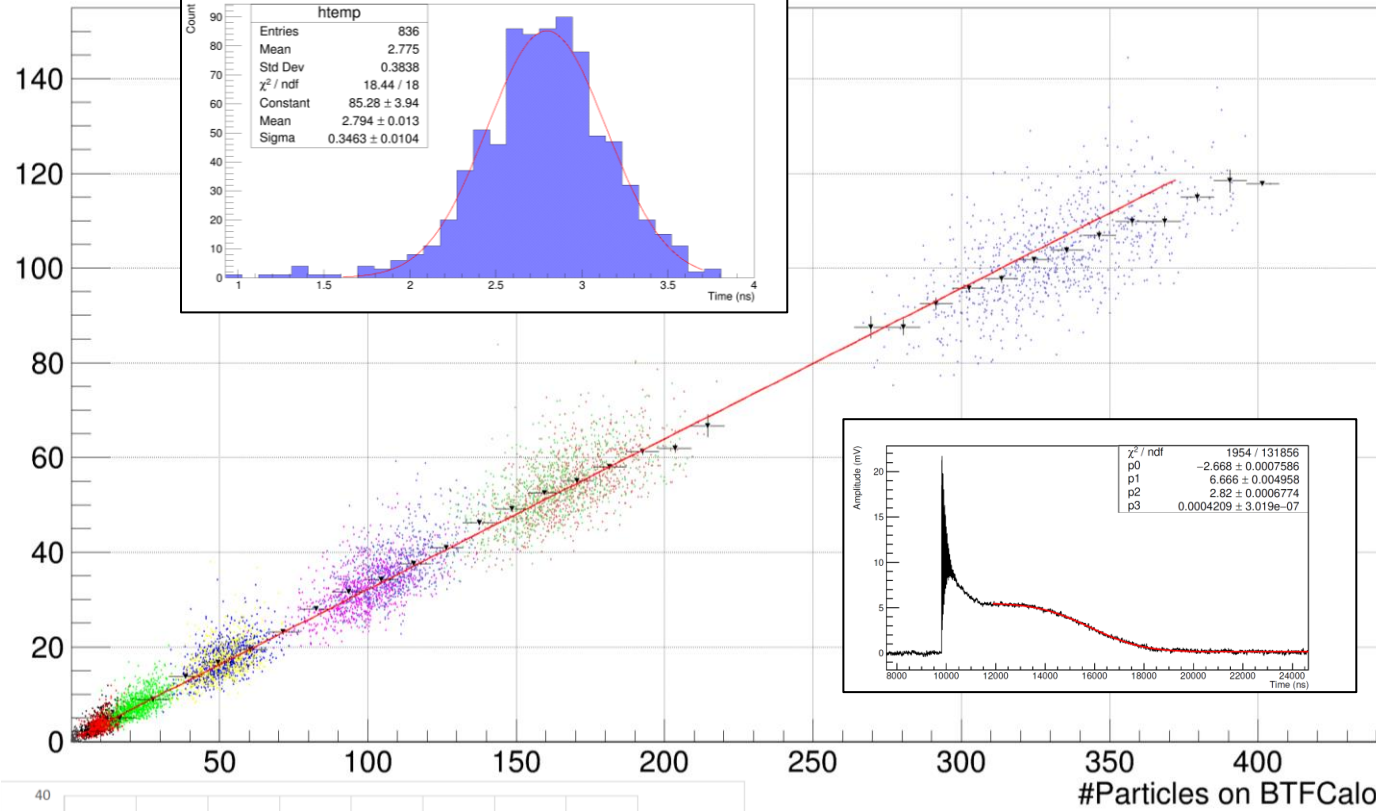
-> Further studies are needed to optimize electrode metallization in order to maximize charge collection without loss of acceptance and time response.

-> 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)

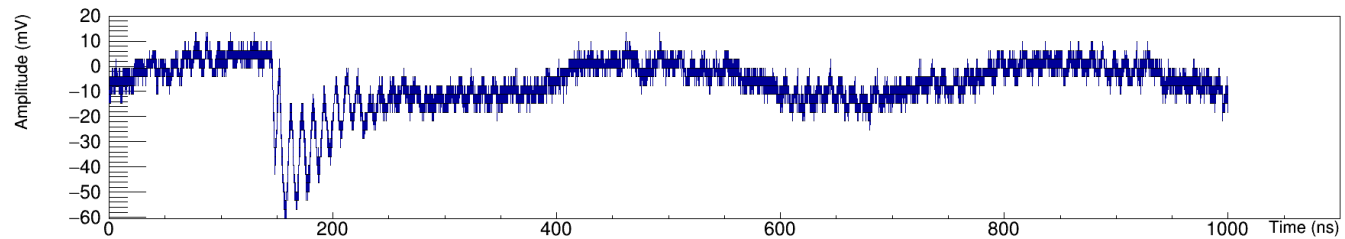
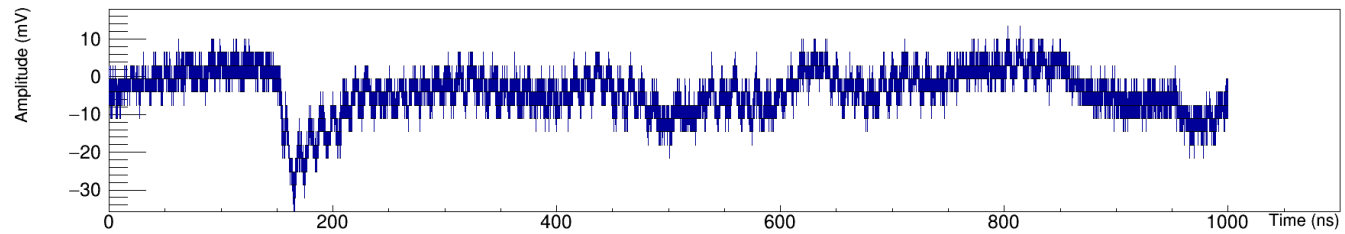
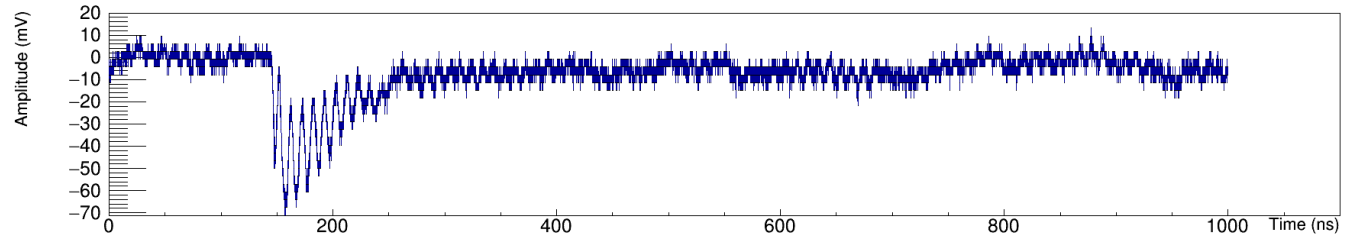
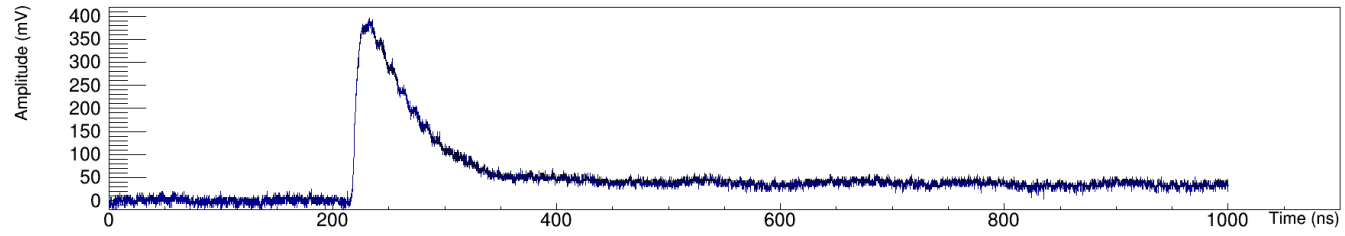


Summary

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 [Ω/cm]	$\gg 10^{11}$	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

