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A high rate and high timing photoelectric detector prototype with RPC structure

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Outline

Background

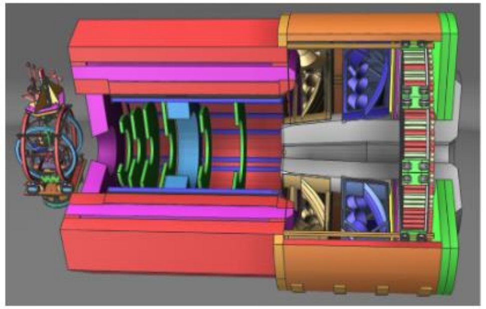
Background

- Future high energy physics experiment:
  high luminosity
  high energy
- Challenges for (gas) detectors:
  high count rates, high time resolution, eco-friendly gases etc.

Motivation

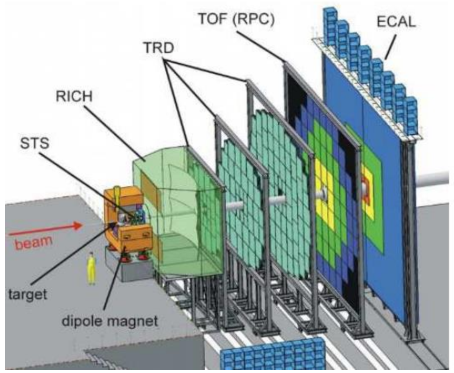
TOF (PID, trigger, background suppression, etc.)

- Working in such condition:
  requirements ($\sigma_t < \sim 30ps$, higher rate > kHz/cm2) → develop a high rate and timing photoelectric gas detector
- Gas detector's limitation (greenhouse effect)→ new eco-friendly gases (low GWP value)



The SoLID apparatus in its first (semi-inclusive deep-inelastic scattering) configuration with the polarized 3He target on the left.

SoLID



CBM

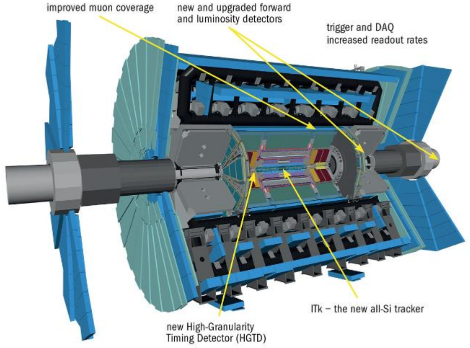


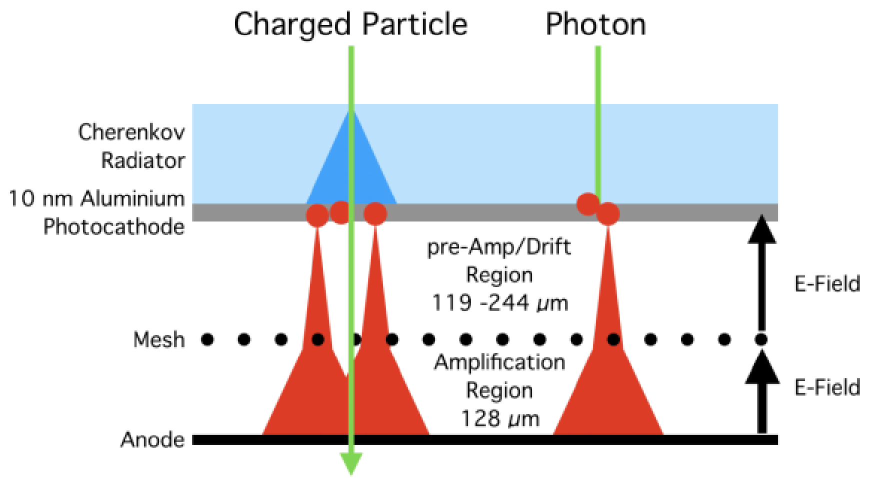
Figure 2: Schematic of the major upgrades to the ATLAS detector for the HL-LHC era. (Image: ATLAS Collaboration/CERN)

ATLAS upgrade (HL-LHC)

Gaseous photodetector

PICOSEC-Micromegas

- MPGD(micro patter gas detector)
- Single photoelectron： $\sigma_t \sim 44\text{ps}$
- IBF~ $\sim\mathcal{O}(10^{-1})$



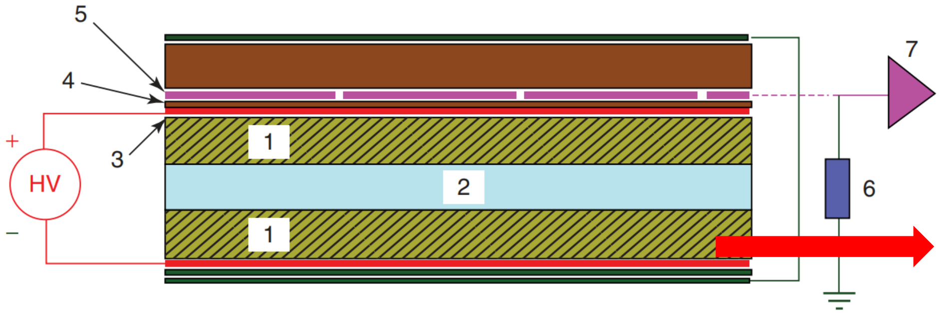
http://dx.doi.org/10.1088/1748-0221/15/04/C04053

RPC-based photodetector

- One electrode → photocathode
  eliminating the position fluctuation of primary e-
- High and uniform electric field: enhances the quantum efficiency, large drift v_{e^-}
- Immediately avalanche of primary photoelectron

better time resolution than PICOSEC, but IBF=1

RPC (σ_t: 10^2ps ~ ns)

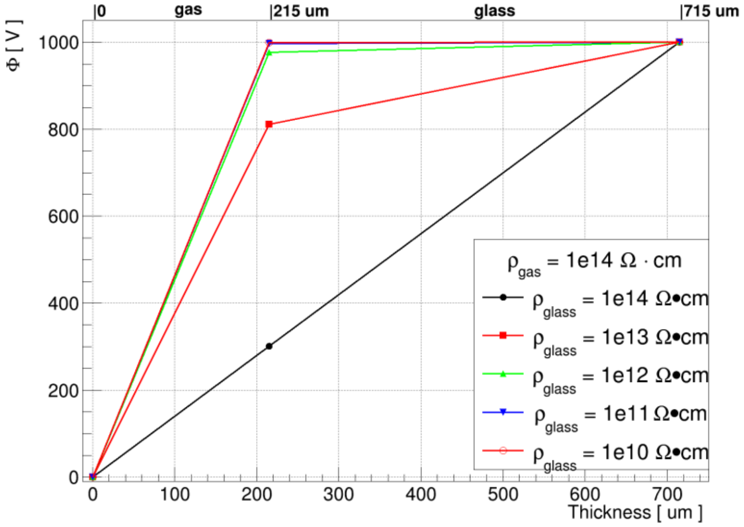


Replaced by photocathode

https://doi.org/10.1002/9783527698691.ch3 P.47

Simulation – Comsol

electric field

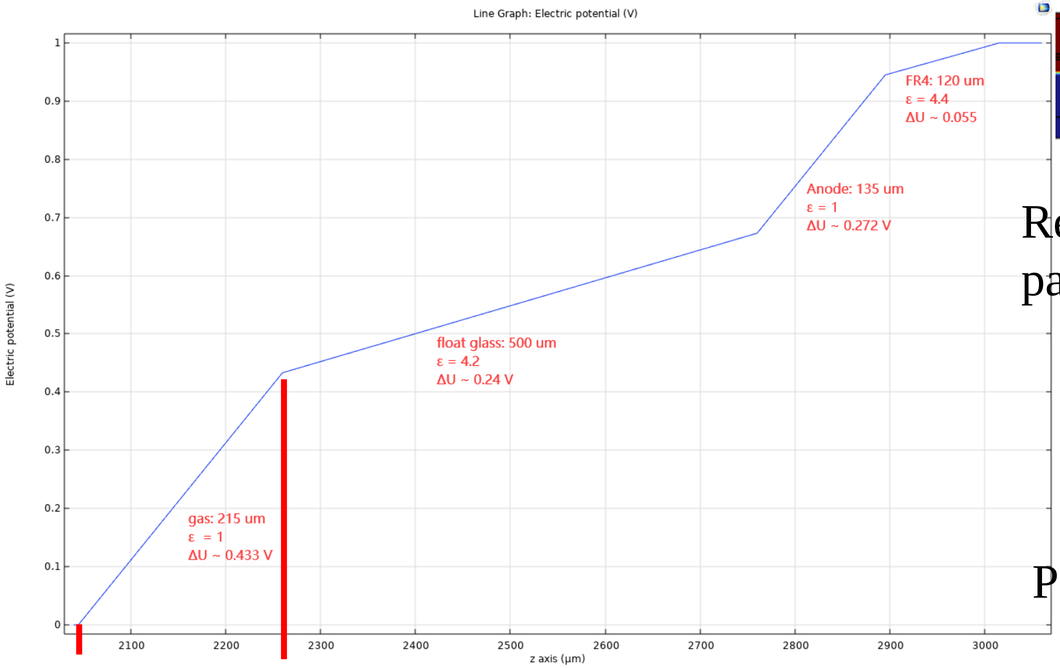


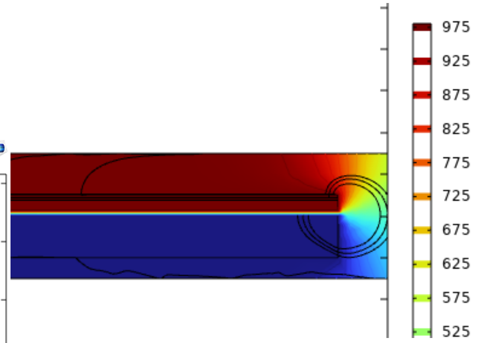
$$\Delta U_{gas} = HV * \frac{\rho_{gas} \cdot l_{gas}}{\rho_{gas} \cdot l_{gas} + \rho_{glass} \cdot l_{glass}}$$

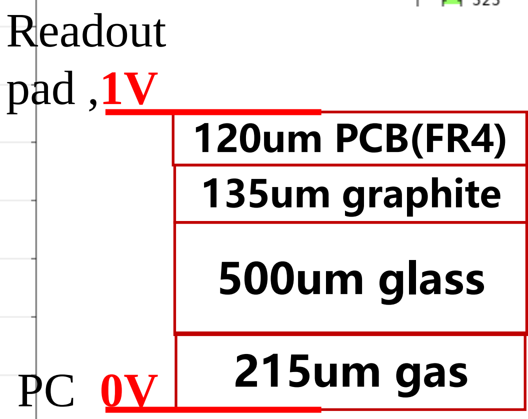
Small current in loop, not electrostatic

$\rho_{resistive\ plate}$↘, Φ_{gas} ↗, E_{gas}↗, Gain↗

weighting field







Ramo's weighting field theorem

$\Delta U_{W-gas} \sim 0.43\ V$

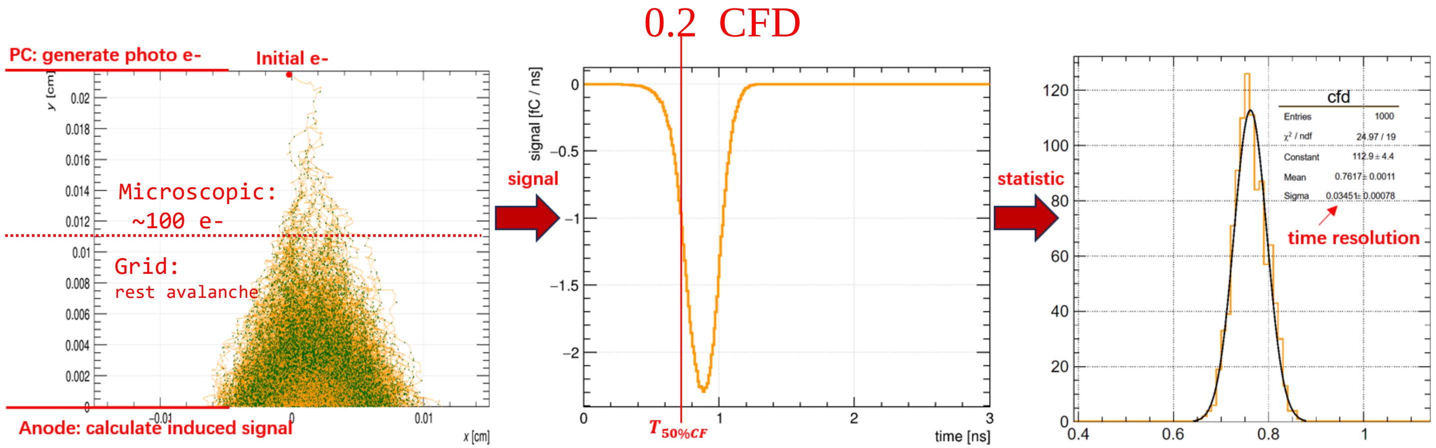
T_{glass}(Thicknees)↘, T_{gas} ↗, ΔU_{W-gas}↗, induce signal↗

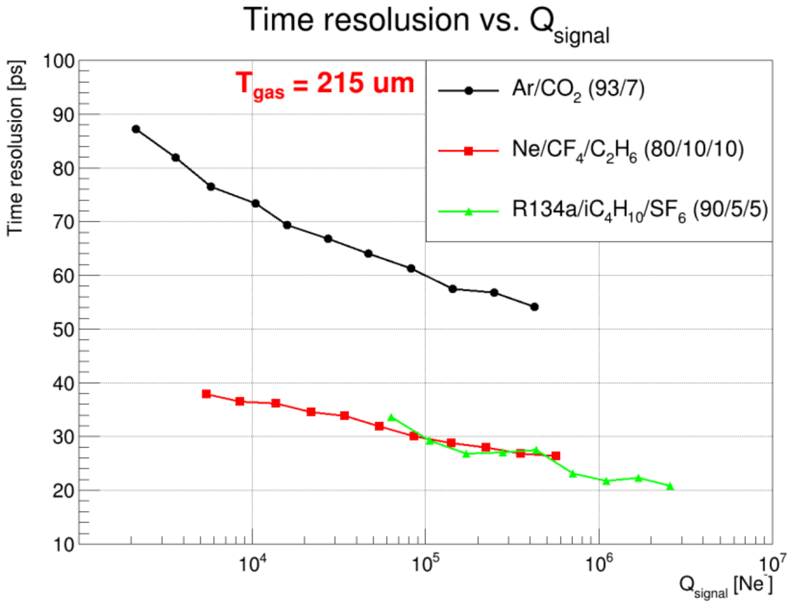
Simulation

Garfield++

avalanche → signal → gain, time resolution, etc.

Uniform filed inside gas, allows for a grid-based MC simulation for the avalanche dynamics (fast simulation)
[RPC | Garfield++ (cern.ch)]





$\sigma_{t-single\ e^-} < \sim\mathbf{30ps}$ @(RPC/Compass gas, 215um)

Experiment

Detector design and install

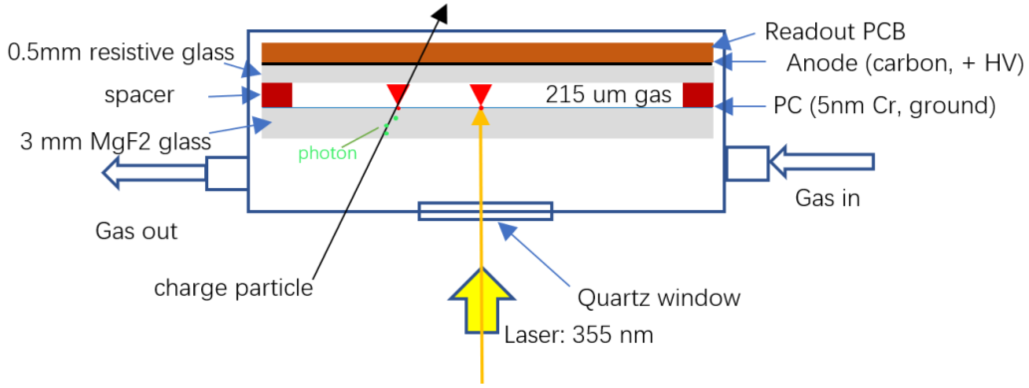


Figure 1: Schematic design of detector.

- Resistive glass: 0.5 mm
- Gas gap: 215 um
- Photocathode: 5nm Cr, in lab laser test, use ordinary quartz glass replace MgF2.

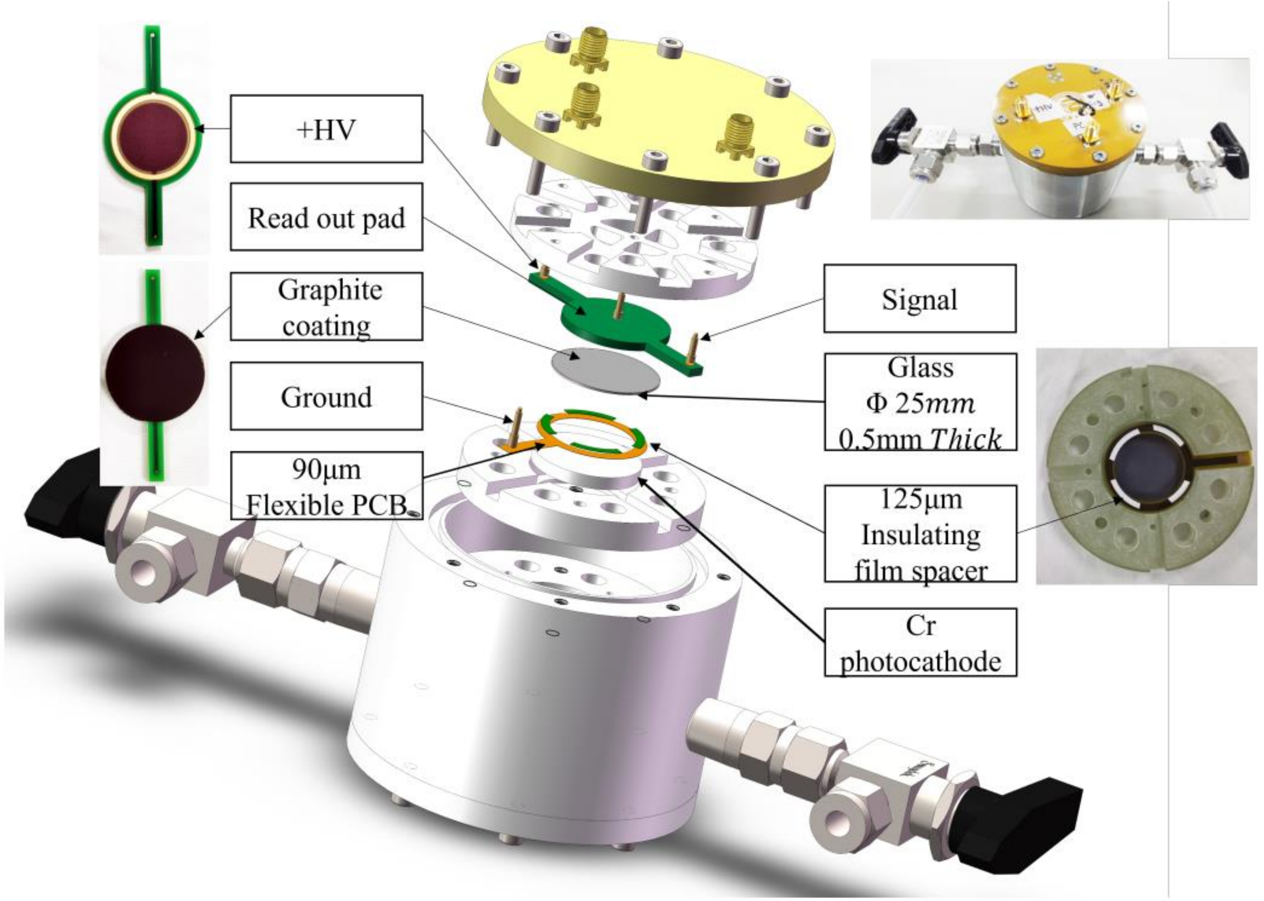
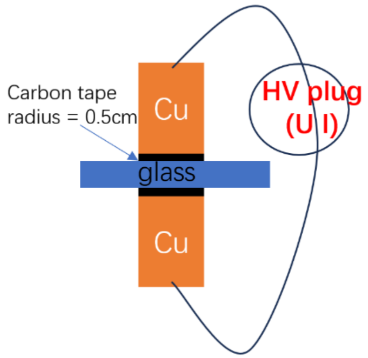


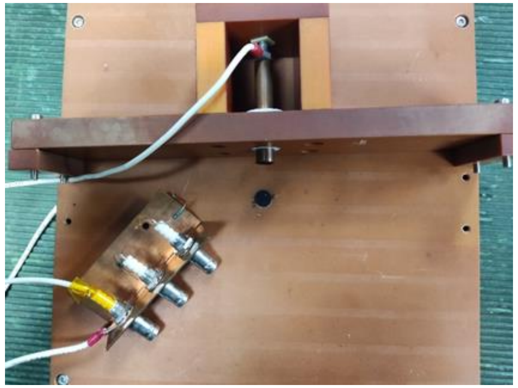
Figure 2: Exploded view and photographs of the detector.

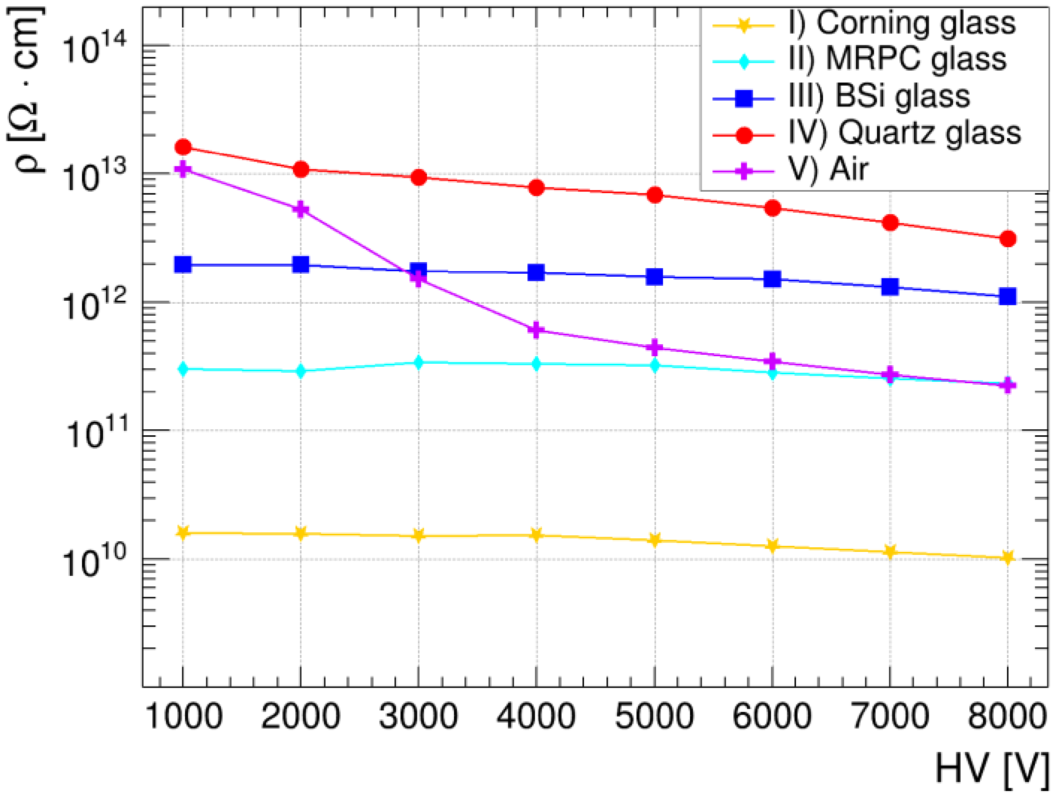
Resistivity materials — float glass

Resistivity test

Several types of float glass
Diameters = 25mm, thickness = 0.2mm, 0.3mm, 0.5mm







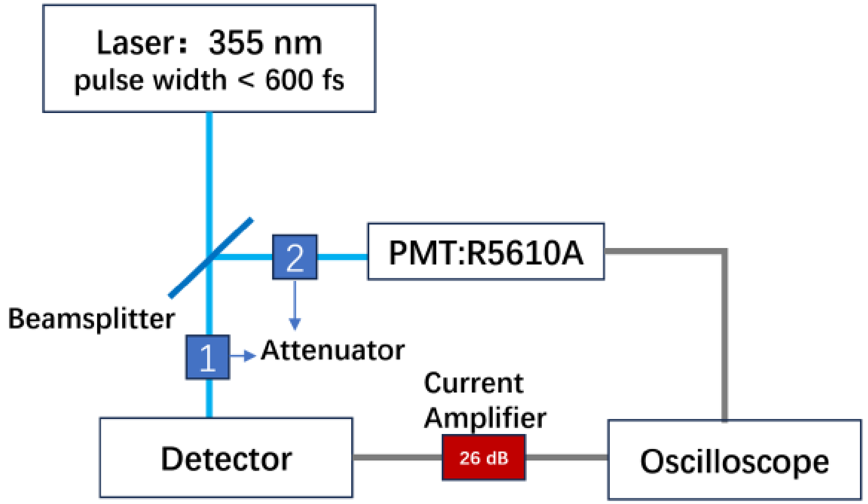
U=IR, $R = \frac{\rho l}{S}$ $\Rightarrow$ $\rho = \frac{U[voltage]}{I[current]}\frac{S[area]}{l[thickness]}$

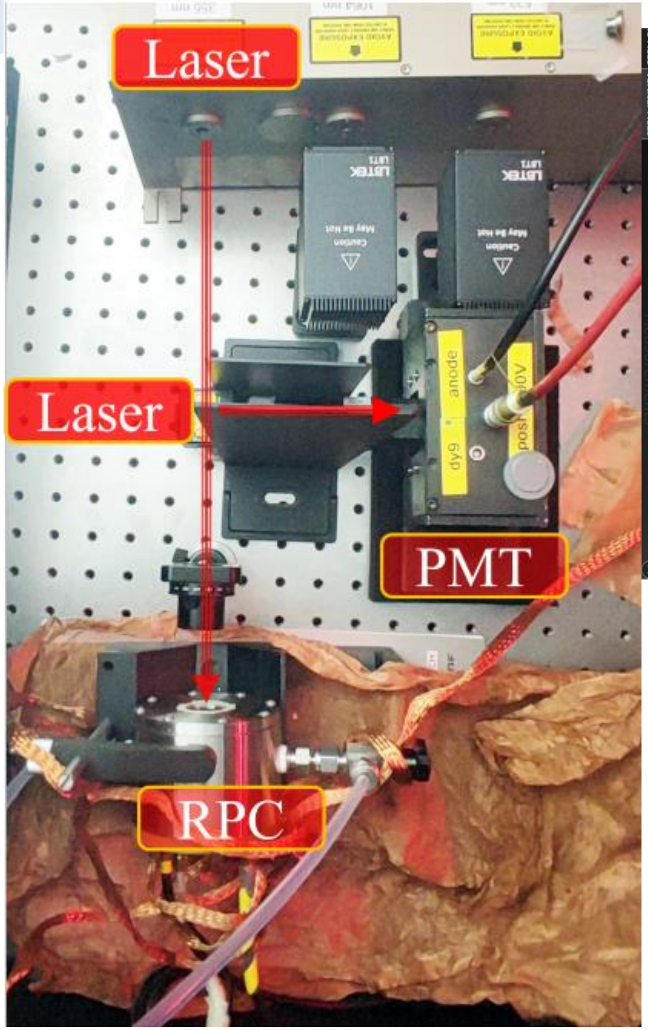
HV↗, ρ↘

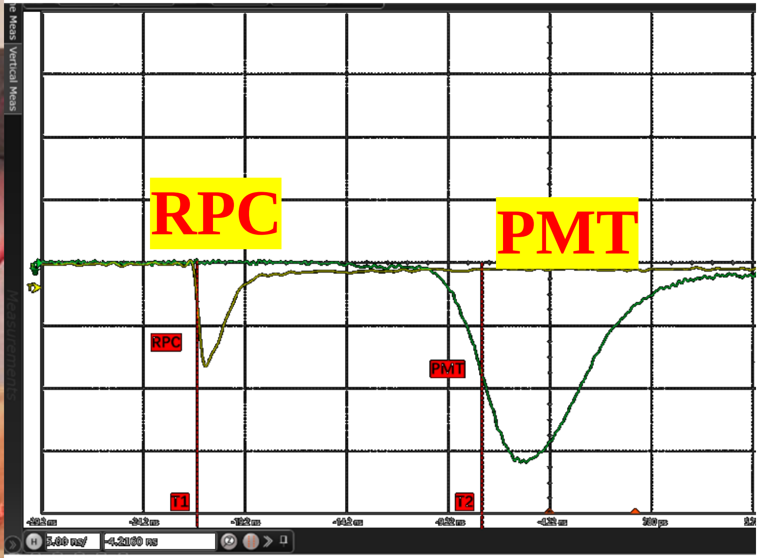
$\rho_{working\ gas} > \rho_{air} \sim 10^{13}\Omega \cdot cm$

Test system

Setup in darkroom







f_{laser}: 1Hz~1000Hz
Change laser intensity by adjusting attenuator 1,2
Two signals are collected on the oscilloscope.

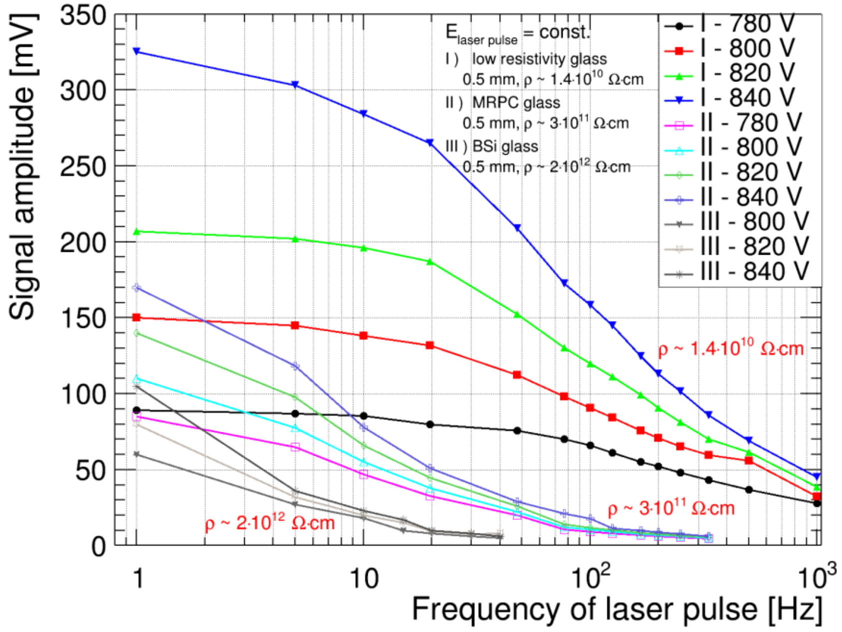
System's time uncertainty:

$\sigma_{system} \sim \sigma_{PMT} \sim 10ps$

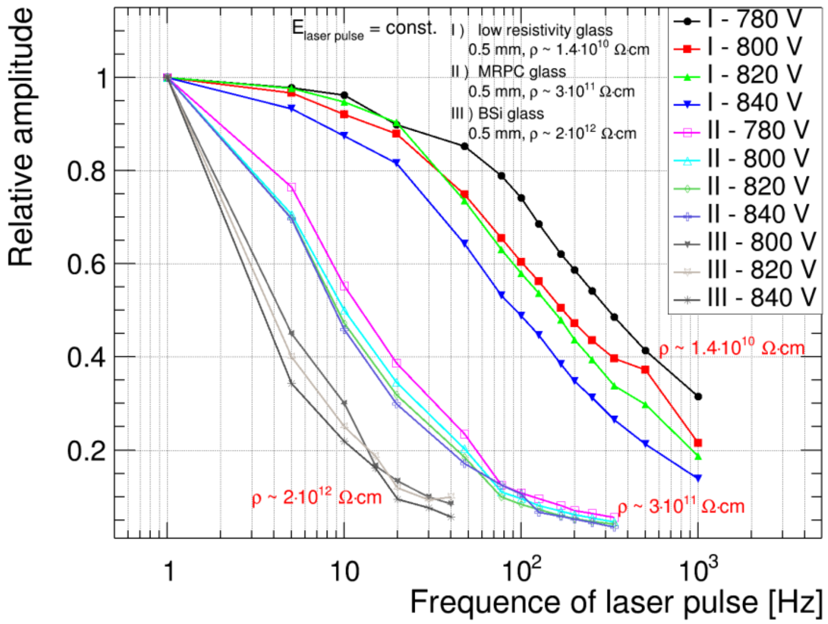
Rate capability of different ρ_{glass}

Test amplitude of RPC signal

Fix E_{laser}, so the number of primary photoelectrons stays the same.
Test A_{RPC} with different glass in Ar/CO2(93/7) as a function of pulse frequency.



Real amplitude



Max amplitude = 1

- At same HV:
  ρ_{glass} ↗, A↘, means smaller E_{gas}
- For a same glass
  f_{laser} ↗, A↘, and
  the smaller ρ_{glass}, the slower A decreases.

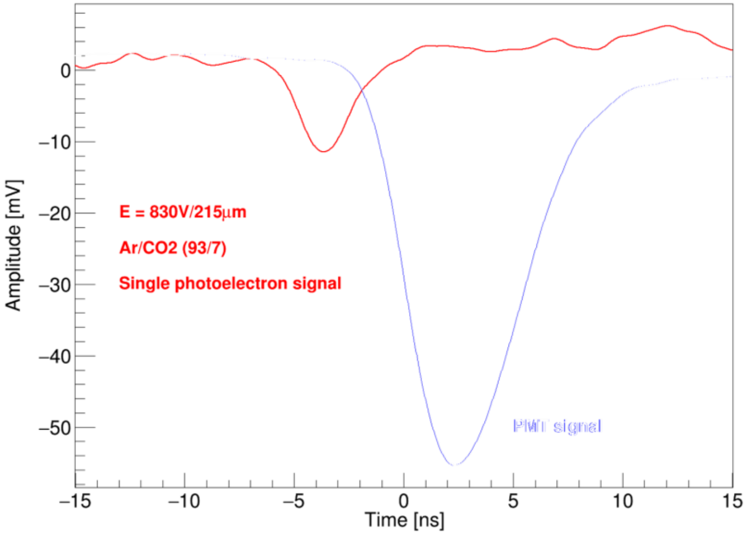
In the later tests, the low resistivity float glass ($1.4 \cdot 10^{10}\ \Omega \cdot cm$, thickness = 0.5 mm) was used.

Single-photoelectron test

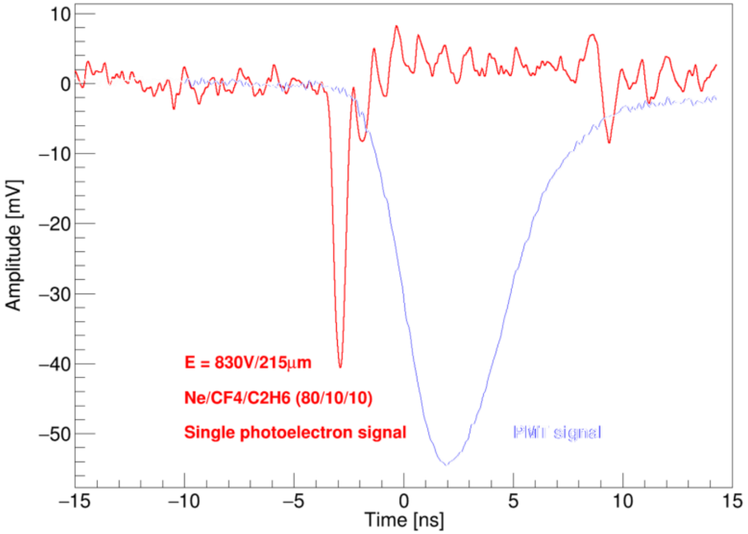
Single-PE signal when $\frac{f_{RPC}}{f_{laser\ pulse}} < 0.1$

Typical signal of single-photoelectron collected by oscilloscope.
Signal amplitude, width, rise time are obviously different in different gas.

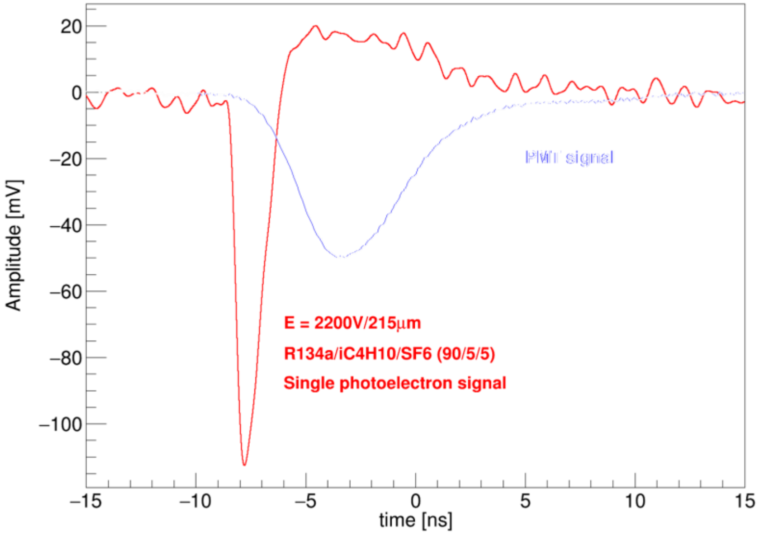
Ar/CO2(93/7)
2 GHz BW due to big S/N



COMPASS gas
Ne/C2H6/CF4(80/10/10)



MRPC gas
R134a/iC4H10/SF6(90/5/5)

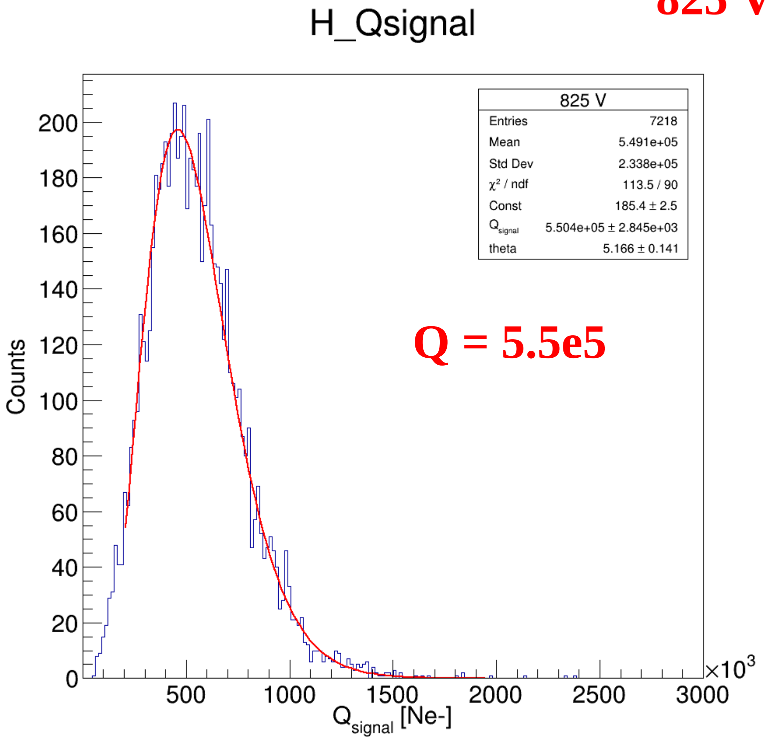


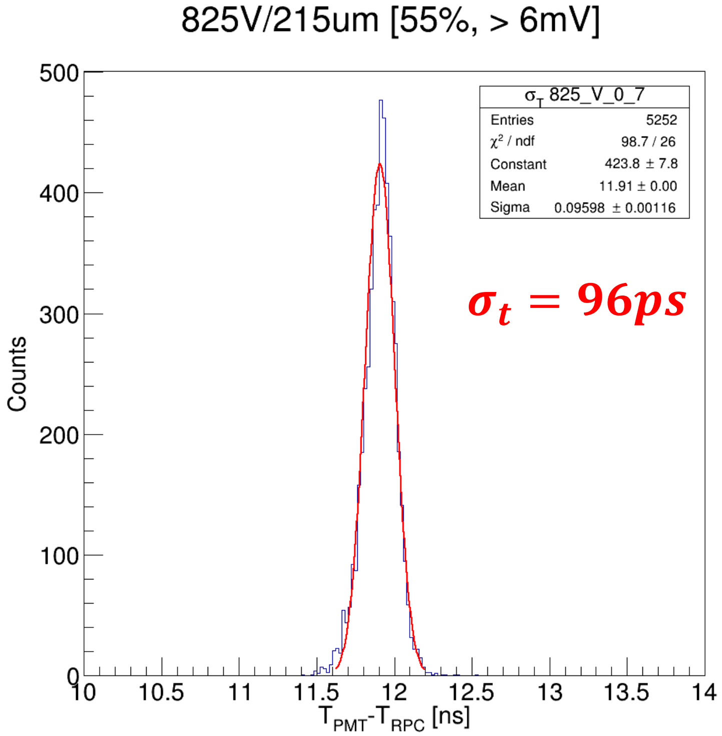
Time resolution – Ar/CO2(93/7)

CFD: constant-fraction discrimination

$$\sigma_{RPC} = \sqrt{\sigma_{total}^2 - \sigma_{system}^2(10ps)}$$

825 V





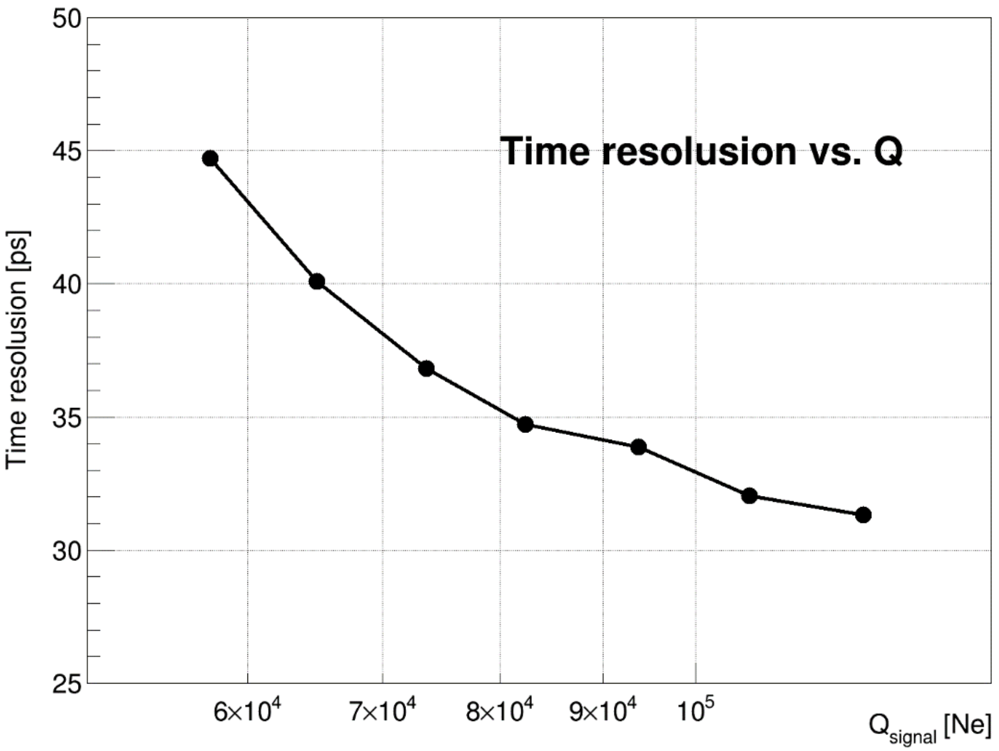
CF_{RPC} = 0.55， A>6mV		
HV[V]	A_{signal}[Ne]	Time resolution[ps]
775	2.3e5	121.9
800	4.4e5	100.0
825	5.5e5	96.0
850	4.8e5	100.9

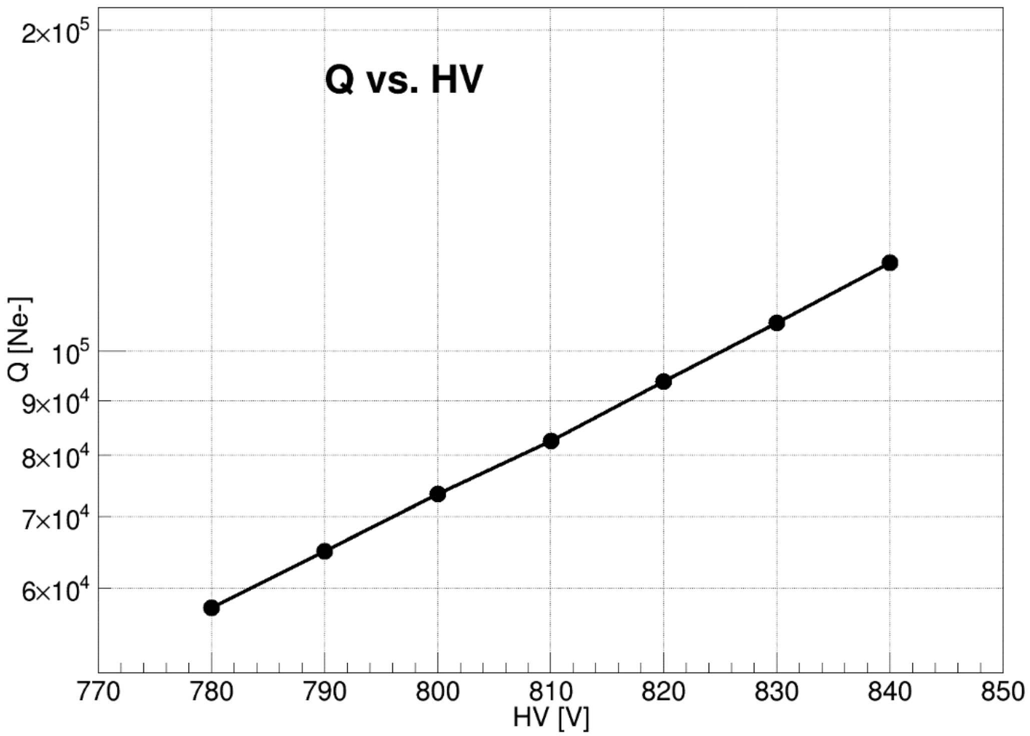
σ_t best to 96ps at a gas gain of 5e5.
Ar is not a good working gas, A_{signal} is too small, noise has a big influence, damages time resolution.

Time resolution – COMPASS gas

Ne/C2H6/CF4(80/10/10)

$CF_{RPC} = 0.55$

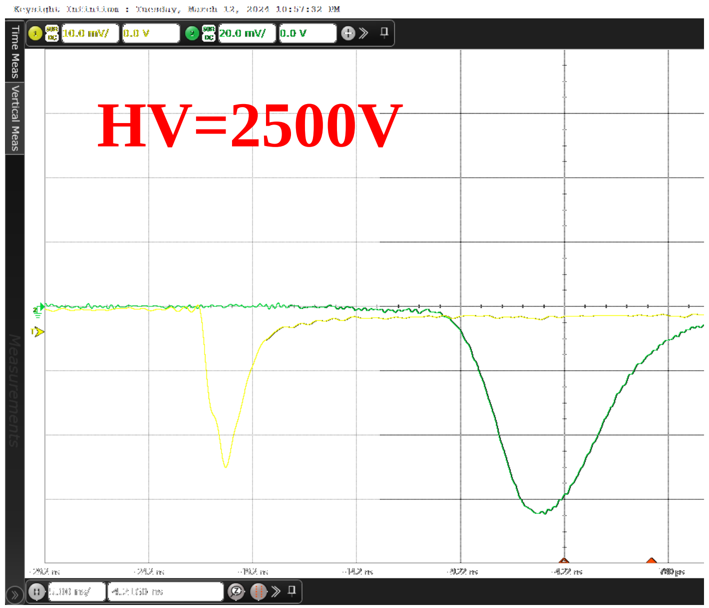


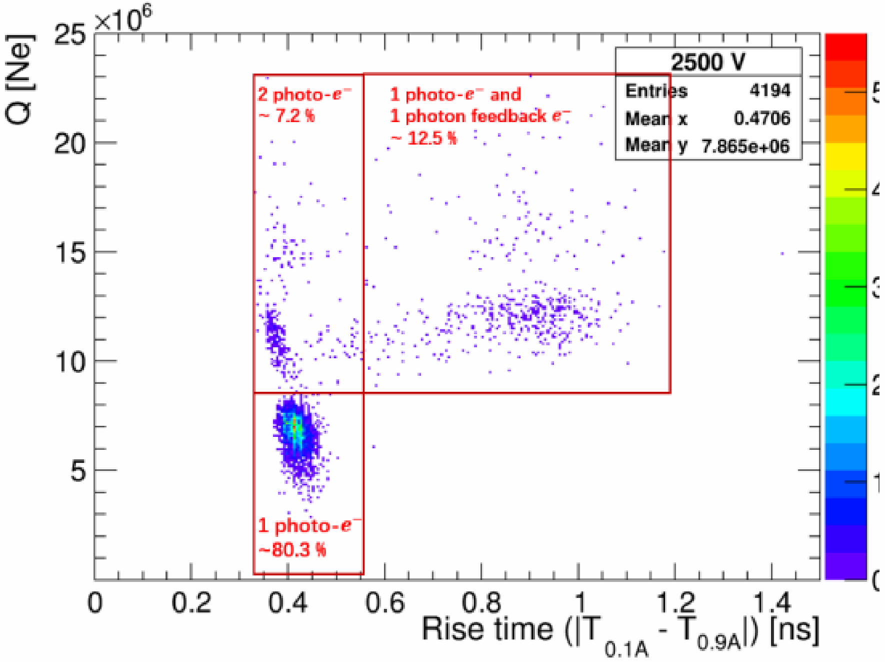


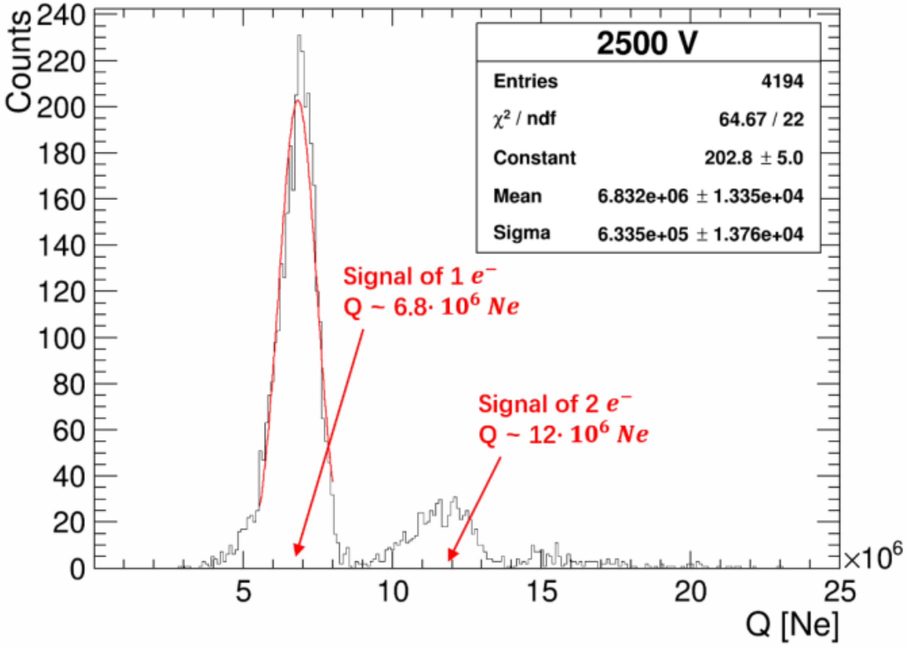
$\sigma_{NPE=1}$ = 45~31ps at a gas gain of 6e4 ~ 2e5.

MRPC gas: photons feedback

R134a/iC4H10/SF6(90/5/5)







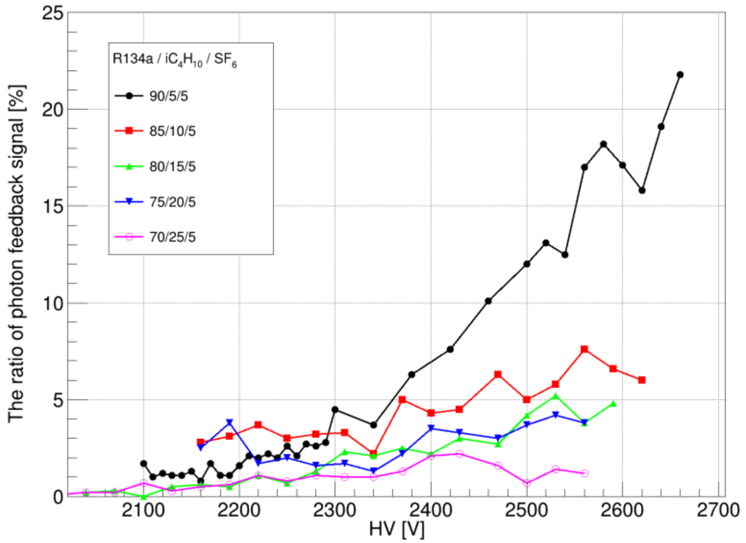
“Double peak”, caused by photon feedback: at high HV, UV photons are produced and excited PC or gas to generated a new photoelectron, create a new avalanche.

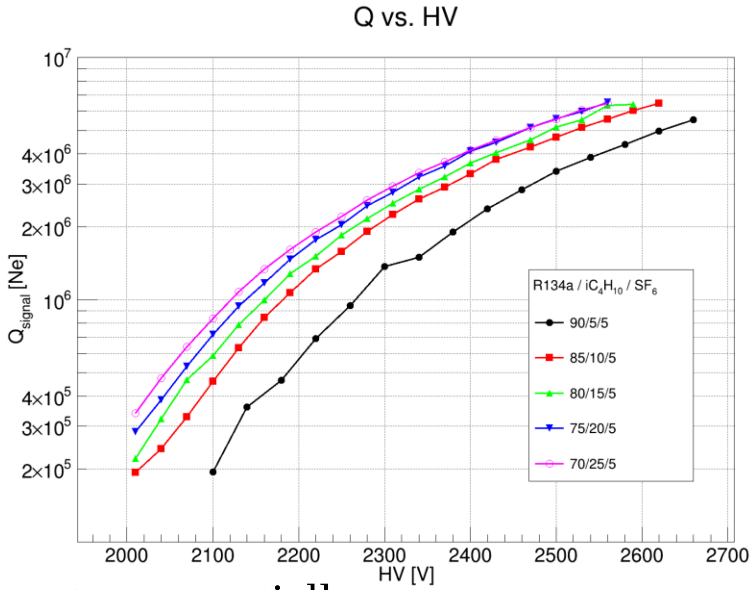
This will make the width and rise time of the signal larger, which is bad for time resolution.

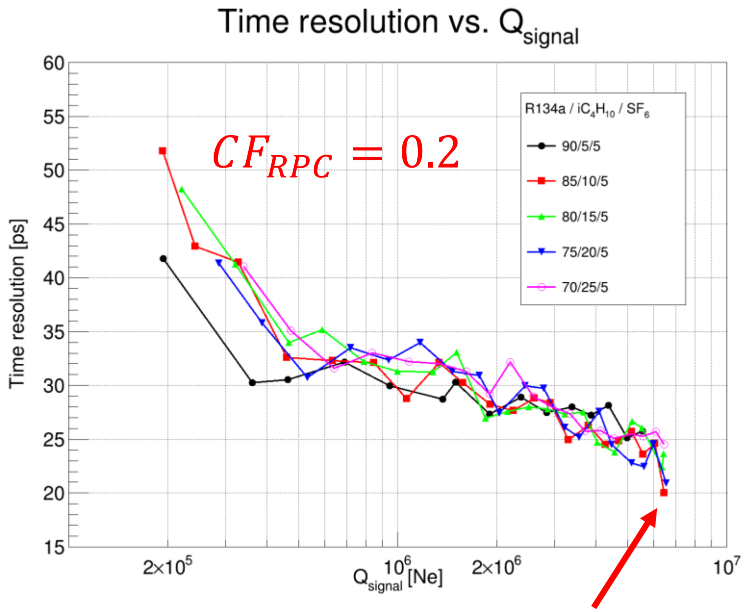
Reduce photon feedback

Fix SF6 = 5%

Select signals of only one primary PE.







~20.3ps

not exponentially, space charge effect

Increase the proportion of iso-butane can effectively reduce photon feedback.

- Increase iso-butane(decrease R134a):
  1 Greater gain at same HV
  2 The max working voltage became small
  3 No significant change in the time resolution
  $\sigma_{NPE=1}$ best to ~20.3ps (85/10/5)

$\sigma_{\mathrm{NPE=1}}$ = 50 ~ 20 ps at a gas gain of 2e5 ~ 7e6.

IV Eco-friendly gas test

Test the single-PE performance

gain, time resolution, working voltage

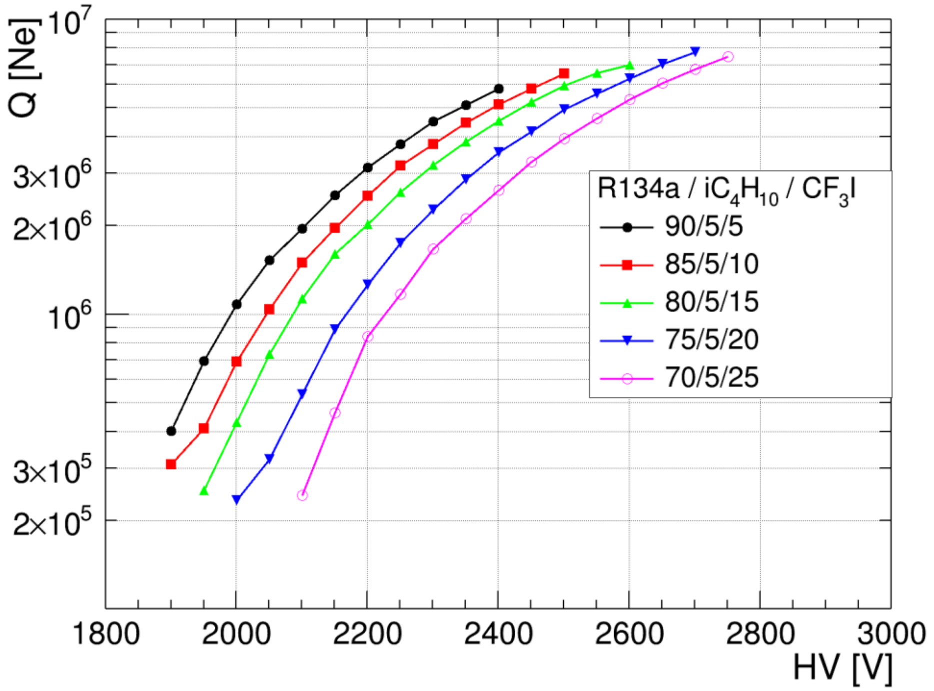
Gas	formula	GWP
R134a	CF3-CFH2	1430
R1234ze	CF3-CH=CHF	<1
R1233zd	CF3-CH=CHCl	1
R1234yf	CF3-CF==CH2	<1
Iso-butane	iC4H10	3.3
	SF6	22800
	CF3I	<5

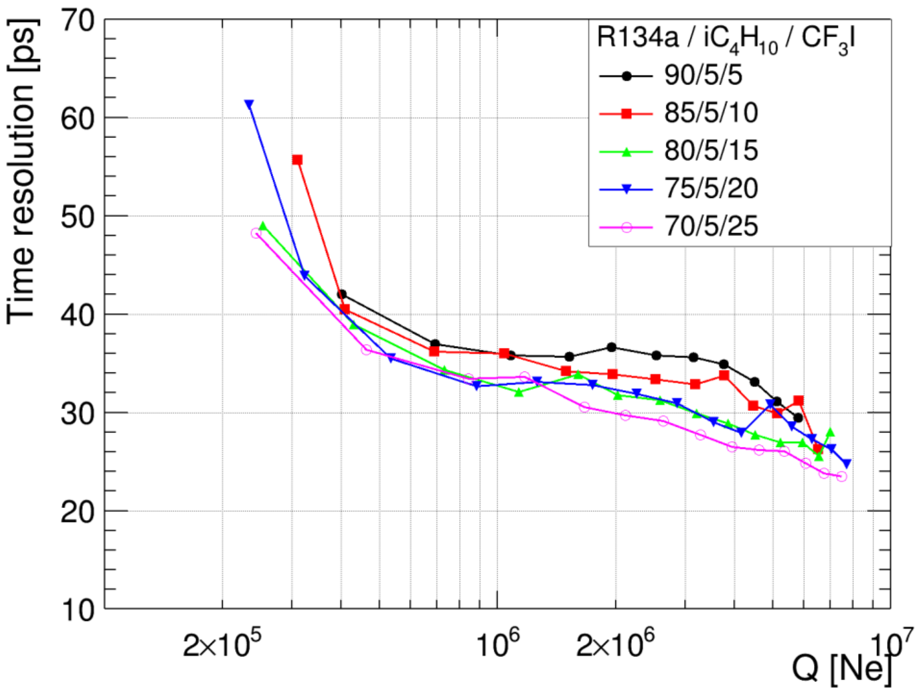
test schedule	
1	R134a/iso/SF6
2	SF6->CF3I
3	R134a->R123ze
4	R134a->R1233zd
5	R134a->R1234yf
6	R134a->R123ze SF6->CF3I

only change the working gas

SF6 → CF3I

Fix iC4H10 = 5%, CF3I = (5,10,15,20,25)%

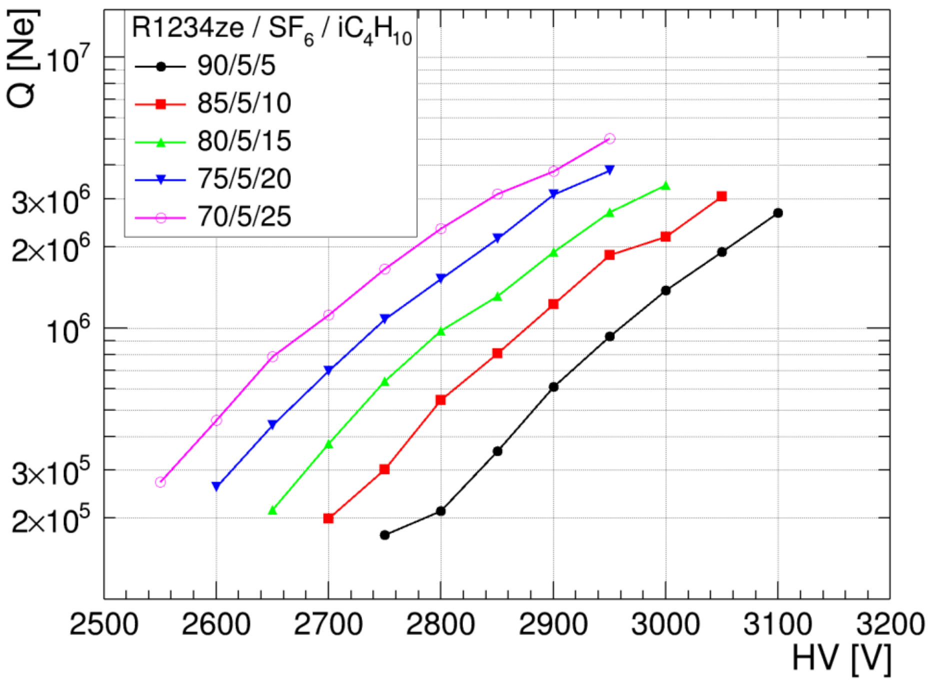


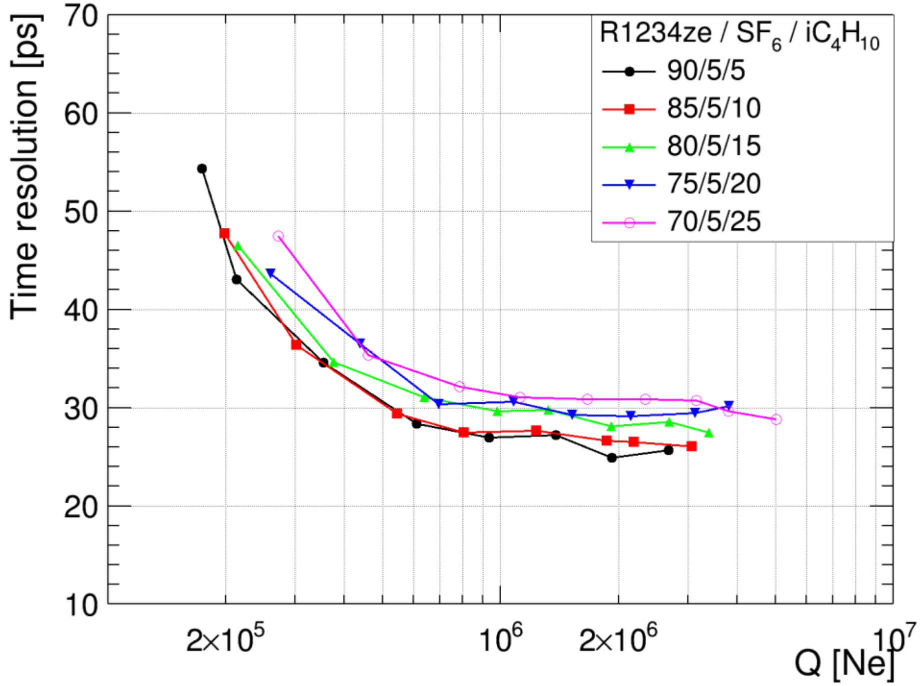


- Increase CF3I: Gain ↘, HV↗, TR↘

R134a → R1234ze

Fix SF6 = 5%, R1234ze = (90,85,80,75,70)%

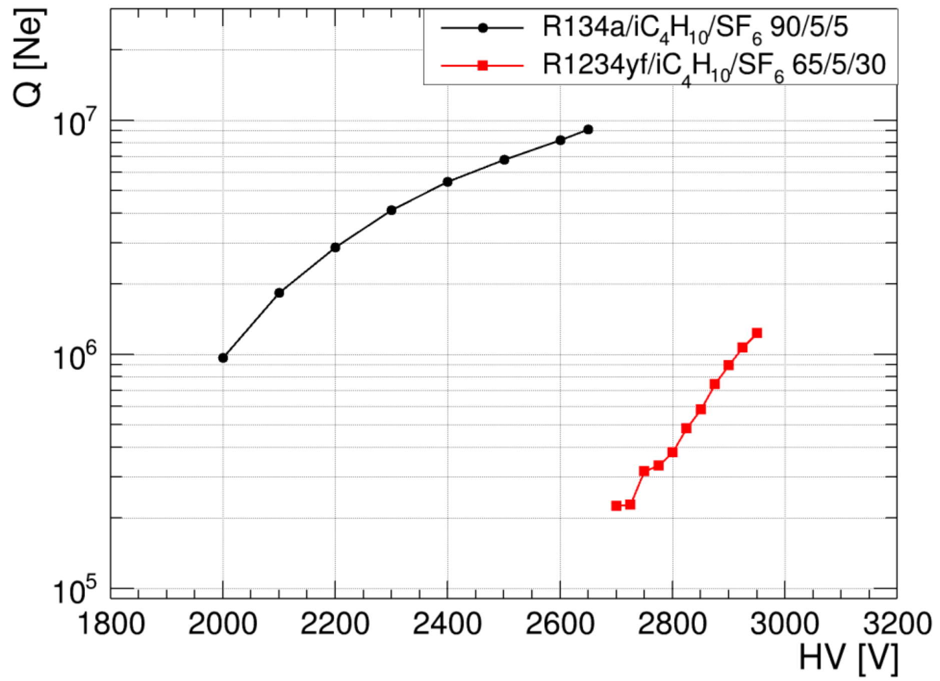


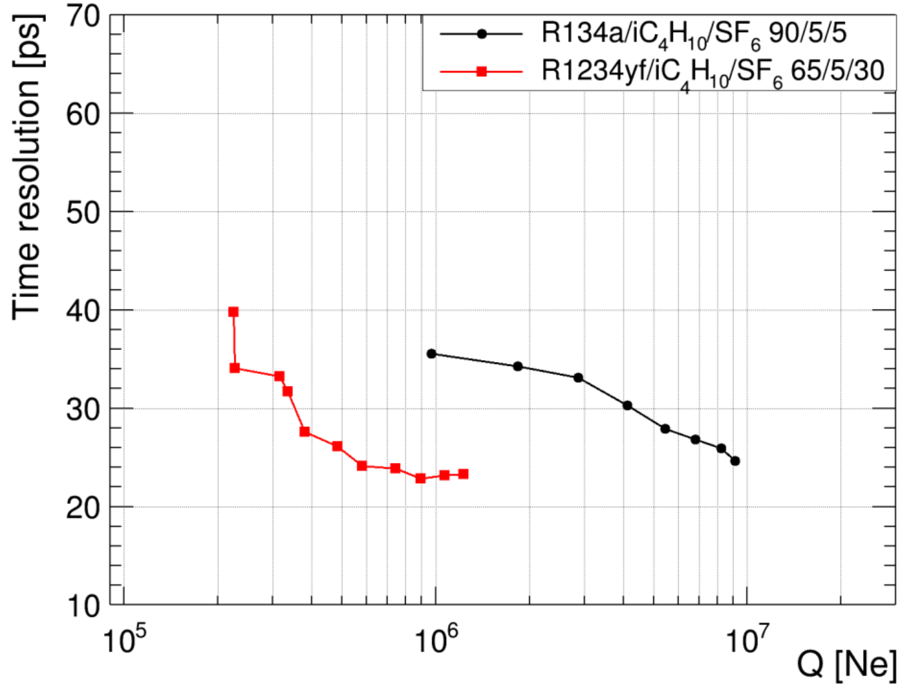


- Increase iC4H10 : Gain ↗, HV↘, TR↗

R134a → R1234yf

iC4H10 = 5%, R1234yf = 65%, SF6 = 30%





R1234yf ratio [%]	discharge HV [V]
90	2300
80	2600
65	3000

- R1234yf: easy discharge.

R134a → R1233zd (<3100V)

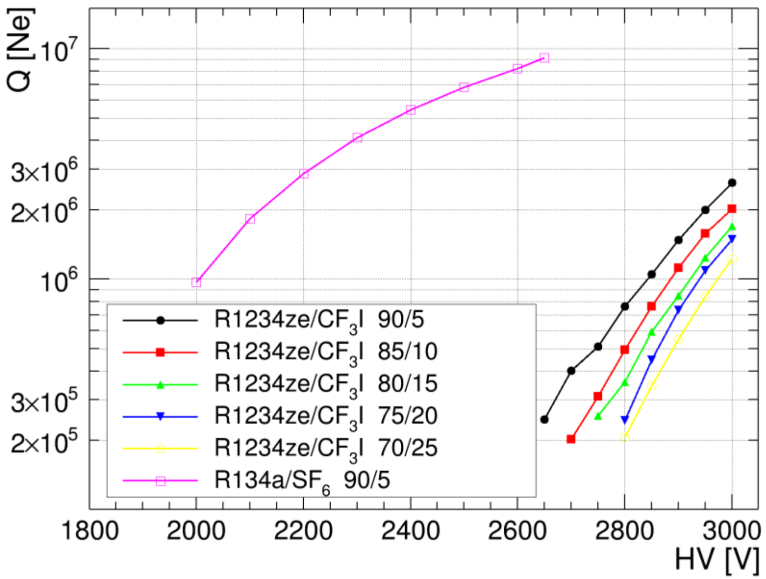
No signal at all, can't work.

(A flat and peaceful curve on oscilloscope until a big discharge at >~3000V)

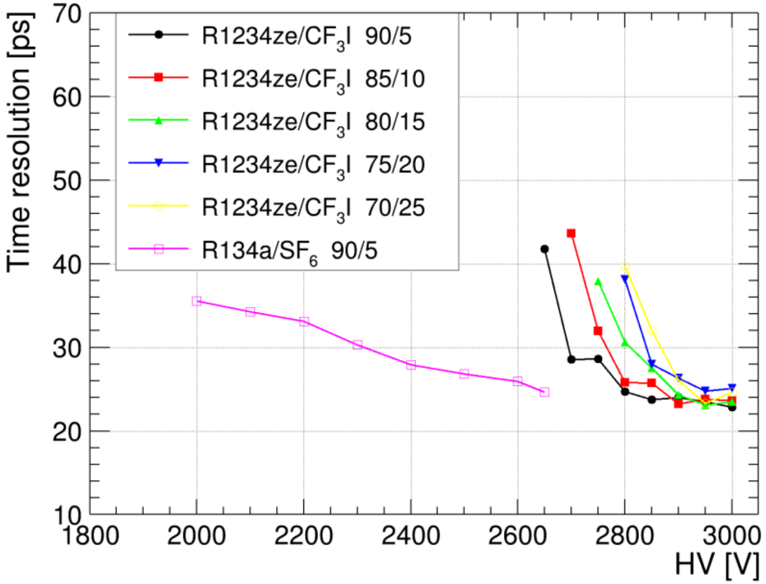
HV power supply turn off (rated I~3 mA),
Normal I_{loop} ~ 10 nA
material breakdown.

R134a → R1234ze, SF6 → CF3I

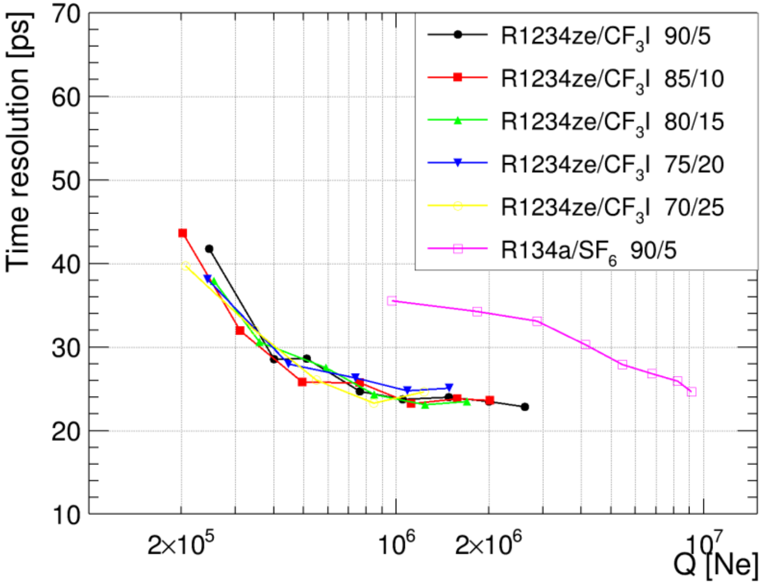
Q(Gain) vs. HV



Time resolution vs. HV



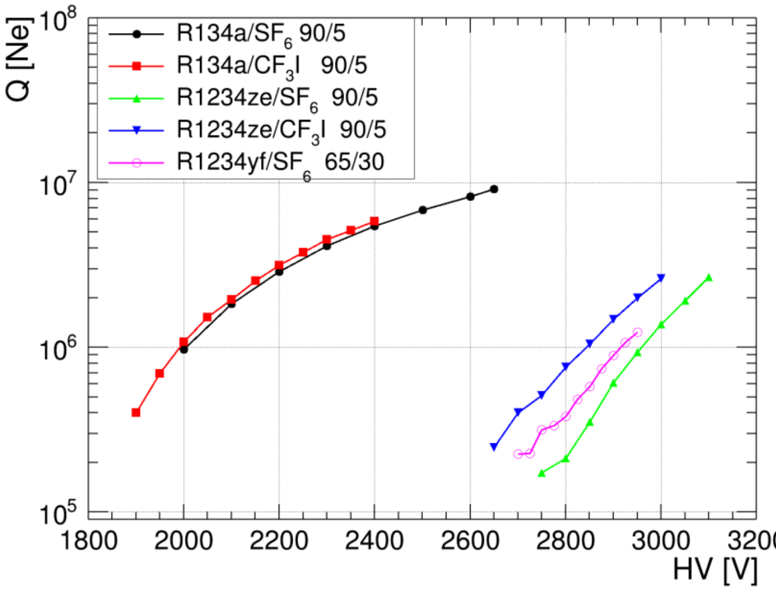
Time resolution vs. Q



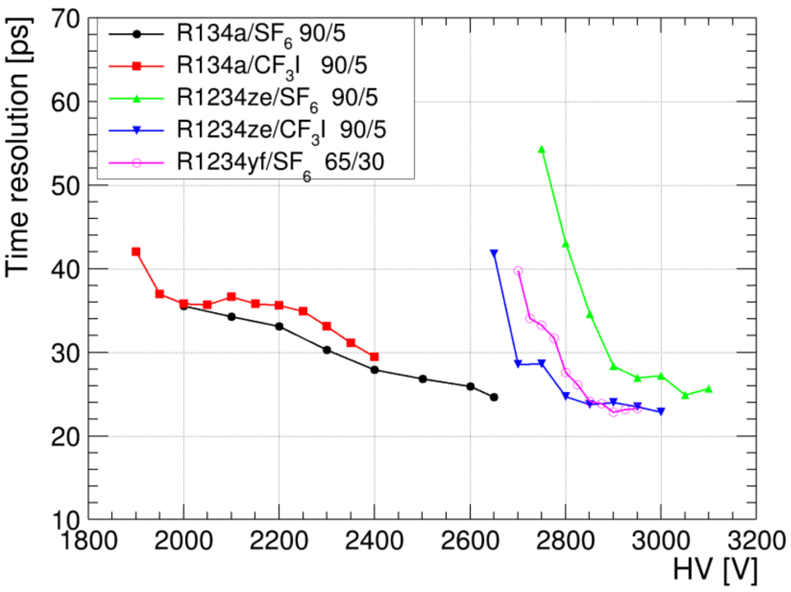
- Increase CF3I : Gain ↘, HV ↗, TR ~unchanged

Result of all gas, fix iC4H10 = 5%

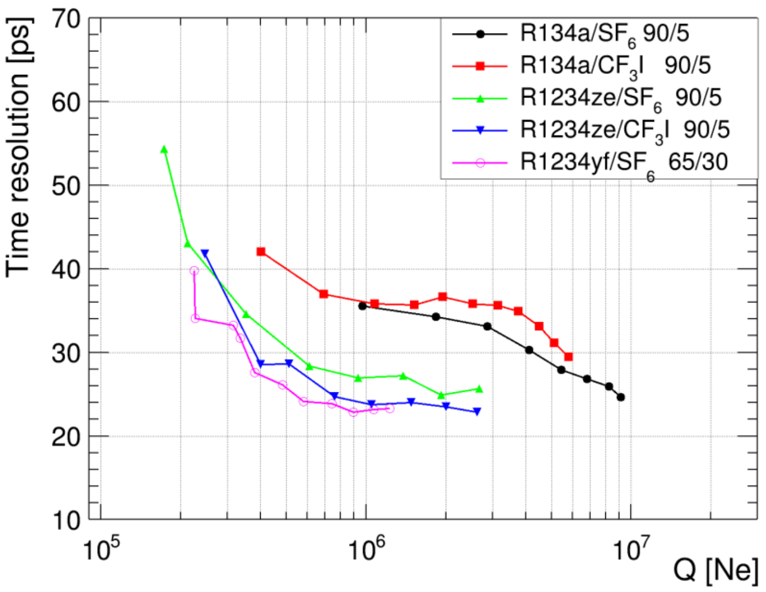
Q(Gain) vs. HV



Time resolution vs. HV



Time resolution vs. Q



R1234ze/iC4H10/CF3I(90/5/5) perform best:
low GWP, good TRvsQ, moderate working voltage

Summary

1. Develop a photoelectric gas detector protype with RPC structure

2. Rate capability improved $10^1 \sim 10^2$ $times$ than typical
   Cheap low ρ float glass: $\rho \sim 1.4 \cdot 10^{10} \Omega \cdot cm$ (typical: $10^{12} \sim 10^{14} \Omega \cdot cm, < kHz/cm^2$)
   (very hopefully for mass production)

3. $\sigma_{t_{NPE=1}}$ = 52~20 ps (Q: 2e5 ~ 7e6) in standard RPC gas
   $\sigma_{t_{NPE=1}}$ = 45~31ps (Q: 6e4 ~ 2e5) in COMPASS gas

4. Eco-friendly gas test:
   R1234ze/iC4H10/CF3I(90/5/5) perform best

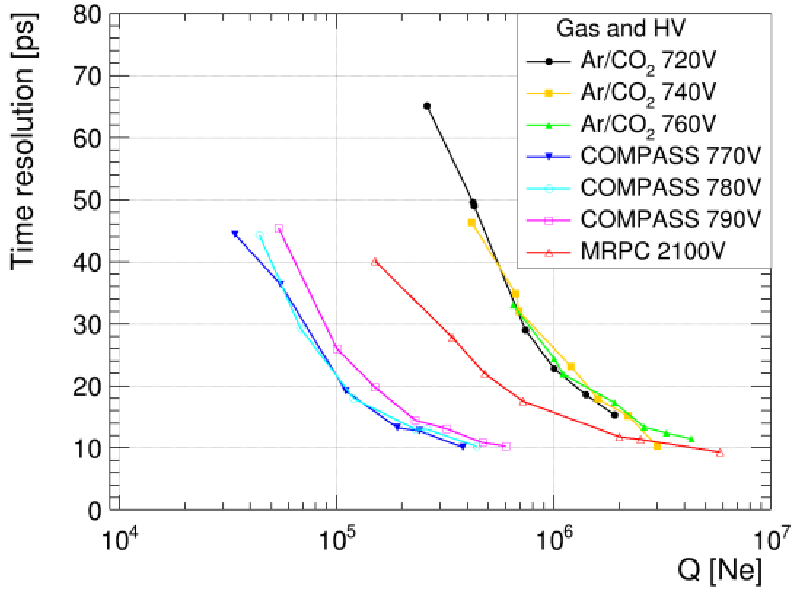
Backup: more gas test

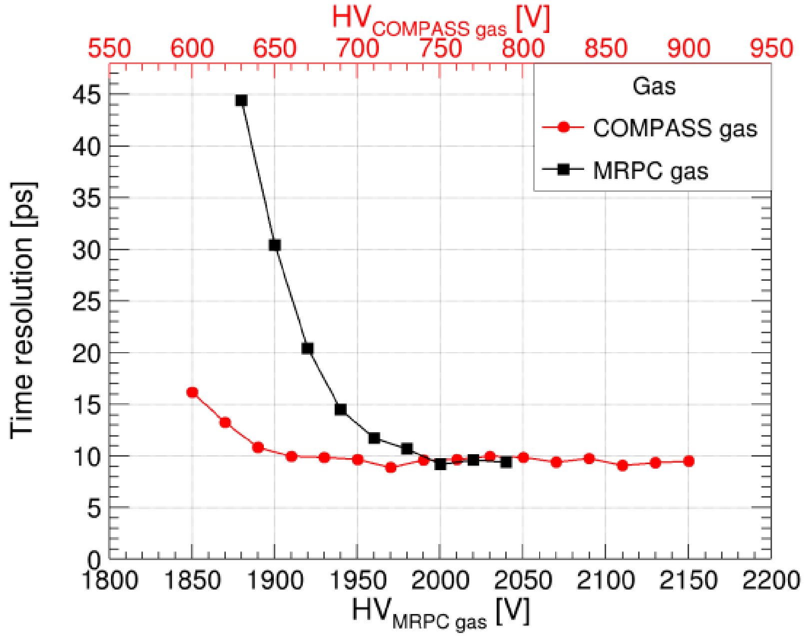
Num	Gas	ratio	Working HV	Time resolution
1	Ar/CO2	93/7	790 ~850	~90
2	Ne/C2H6/CF4	80/10/10	780~840	~30
3	MRPC gas R134a(C2H2F4)/SF6/iC4H10	90/5/5	2100~2750	~29
4		85/5/10	2100~2620	~27
5		80/5/15	2100~2590	~26
		75/5/20	2100~2560	~26
6		70/5/25	2100 ~ 2530	~25
7				
8	R134a/SF6/iC4H10/CF4	70/5/20/5	2100 ~ 2530	~29
9	R134a/SF6/iC4H10/C2H6	70/5/20/5	2100 ~ 2530	~26

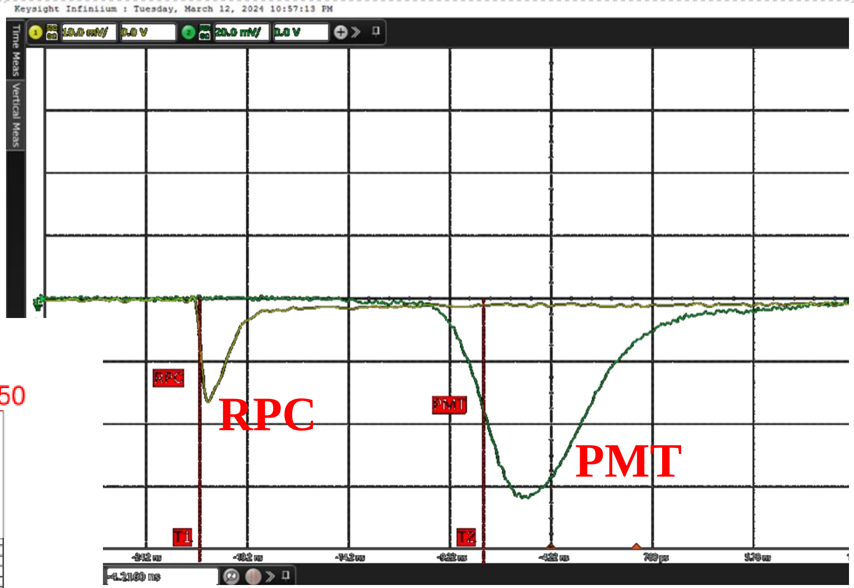
System's time uncertainty

PMT : Voltage = 280V, amplitude ~50 mV without amplifier(many photoelectrons) (keep constant)

Fix HV_{RPC}, increase E_{laser}, or fix E_{laser}, increase HV_{RPC}.



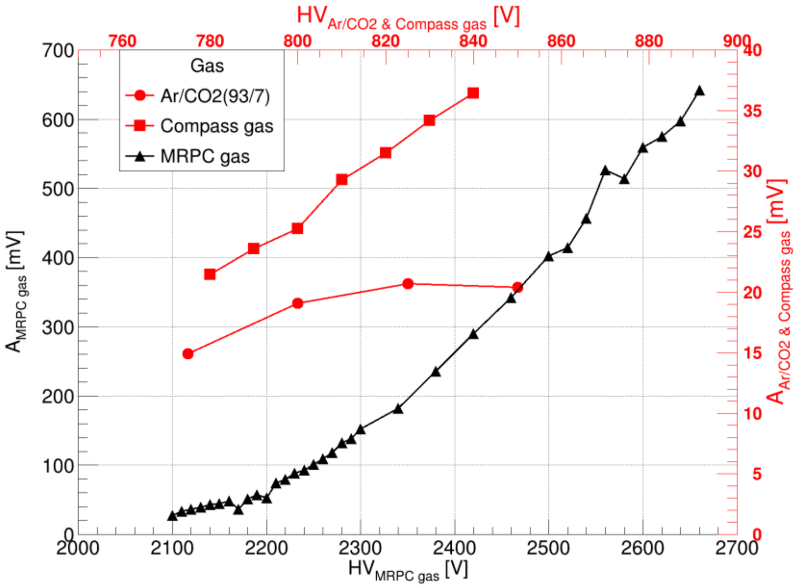


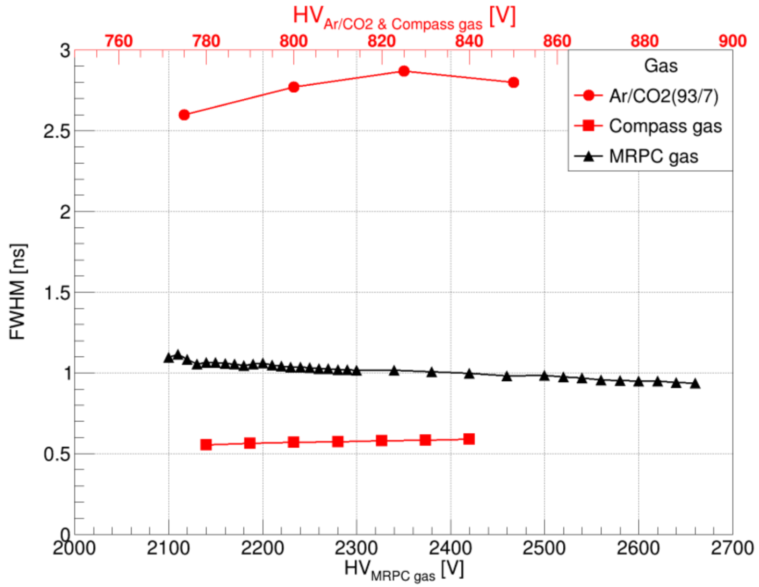


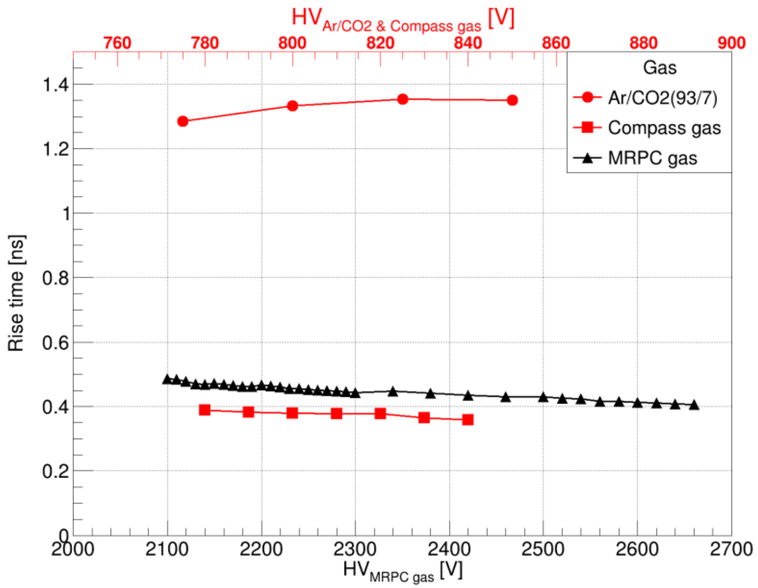
$$\sigma_{system} \sim \sigma_{PMT} \sim 10ps$$

Signal’s characters

Gas	Amplitude(mV) x20	Width[ns]	Risetime[ns]
Ar\CO2	15 ~ 20	2.6 ~ 2.9	1.28 ~ 1.35
Compass gas	25 ~ 38	0.55 ~ 0.59	0.36 ~ 0.39
Compass gas	30 ~ 650	0.94 ~ 0.1.1	0.41 ~ 0.49





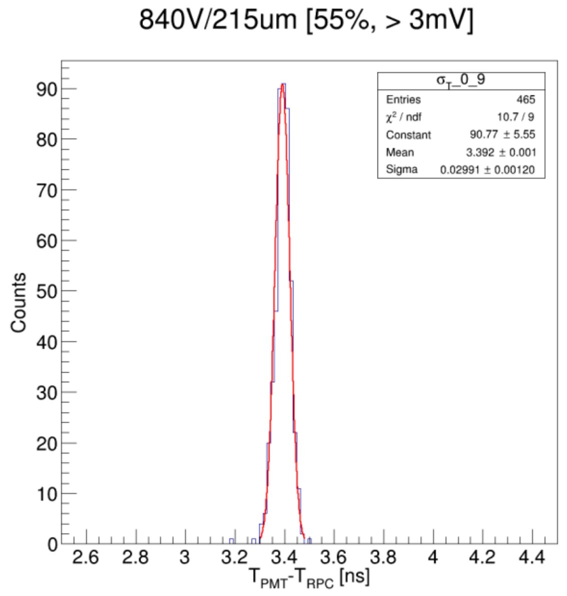


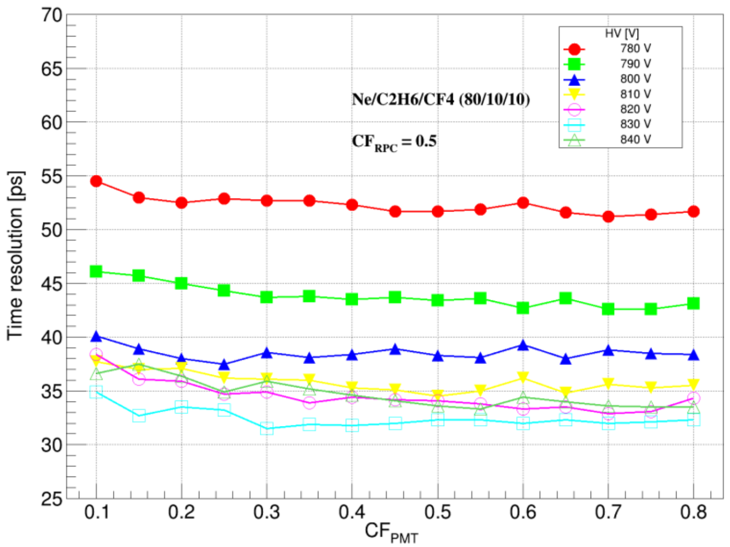
Time resolution of single-photoelectron

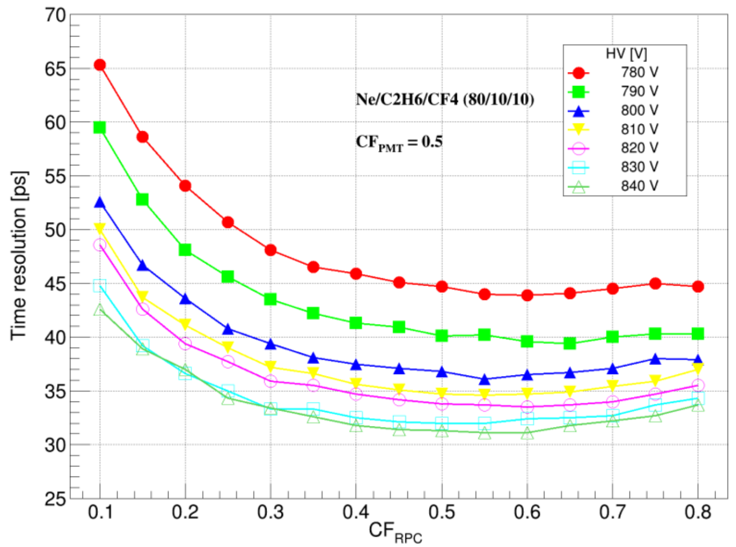
Constant Fraction Timing (CFD)

$\sigma_{RPC} = \sqrt{\sigma_{total}^2 - \sigma_{system}^2(10ps)}$ How to decide CF coefficients? eg: Compass gas

So in Compass gas,
$CF_{RPC}\sim 0.55, CF_{PMT} = 0.5$







Fix $CF_{RPC} = 0.5, change\ CF_{PMT}$

CF_{PMT} has no significant influence.

Fix $CF_{PMT} = 0.5, change\ CF_{RPC}$

$CF_{RPC}\sim 0.55, \sigma_{totla}$ is best.

Eco-friendly gas test – fix iC4H10 = 5%

test schedule	
1	R134a/iso/SF6
2	SF6->CF3I
3	R134a->R123ze
4	R134a->R1233zd
5	R134a->R1234yf
6	R134a->R123ze SF6->CF3I

1 reference
2