Threshold-Dependence Study for Narrow-pitch-strip CMS RPCs

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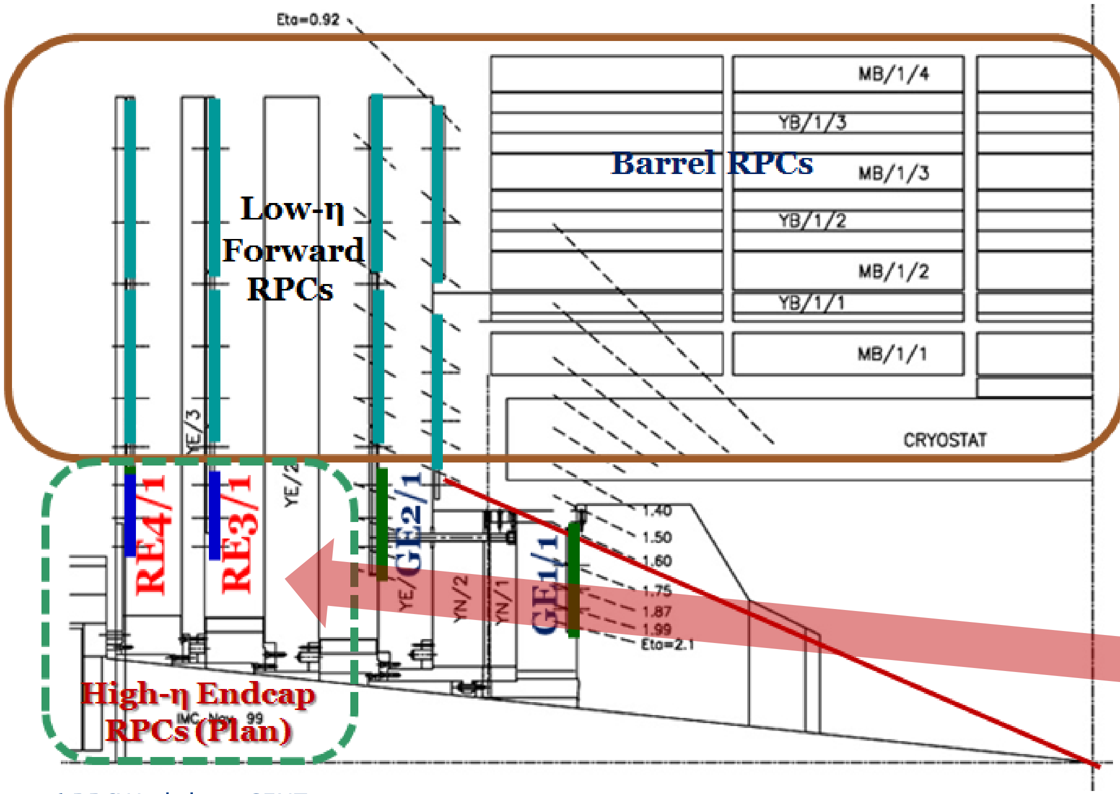
On Behalf of the CMS RPC Collaboration

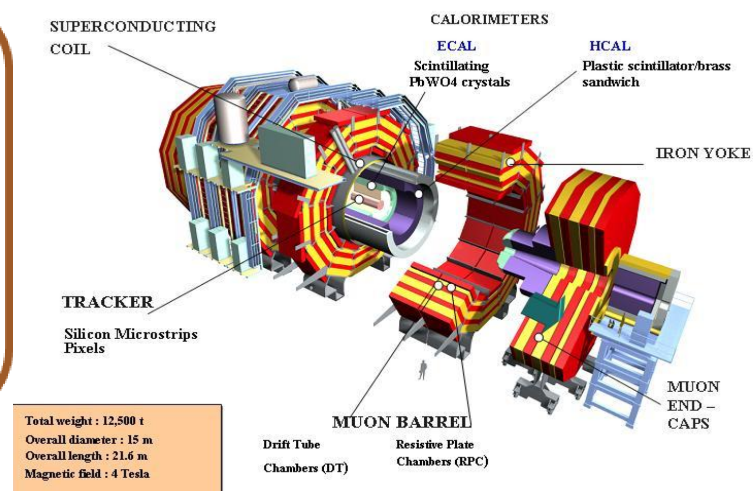
1. Motivation
2. Test of the prototype RPCs at KODEL and GIF++/CERN
3. Conclusions

1. Motivation

The present detector R&D is for future CMS RPCs at high backgrounds

- ✓ In the current CMS muon system, Barrel + 4 endcap RPC stations (+ & -) composed of double-gap RPCs in **|η| < 1.6**
- ✓ In the PHASE I upgrade, 4th RPC station in **|η| < 1.6** has been completed in 2014.
- ✓ In the PHASE II upgrade by 2023, new endcap RPCs in **1.6 < |η| <2.1(2.4)** are currently proposed.





RPCs in high-η to be developed in the phase II upgrade

Direction of R & Ds for the high-η CMS RPCs (at RE3/1 and RE4/1)

We have pursued better detector performance ensuring higher rate capability for the future CMS RPCs:

✓ More sensitive detectors and electronics

→ Better for reducing the probability of aging due to high-rate background

→ To guarantee the better longevity of the RPC gaps

✓ Lower resistivity → **Rate capability ~ 1/ ρ**

Resistive plates for CMS RPCs

✓ HPL (high pressurized laminate): **ρ ~ a few 10^{10} Ω cm**

→ Still, the best choice in virtue of the low unit price.

In the present R&D, two different type RPCs have been suggested and tested at GIF++/H4 and KODEL/KU.

Type A: two 1.6-mm-thick (instead of 2.0-mm thickness) double-gap RPCs

Effective HV = 7.8 ~ 8.4 kV (15% lower compare to that of the current CMS RPCs)

Type B: two 0.8-mm-thick four-gap (multi-gap) RPCs

Effective HV = 9.0 ~ 9.8 kV (~ same with that of the current CMS RPCs)

Advantage → The detector current induced by high-rate particles is four times lower.

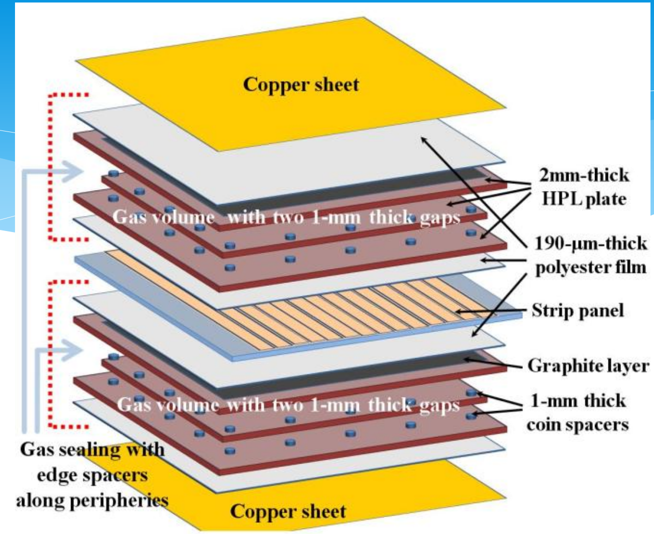
Prototype RPCs tested at GIF++ and KODEL

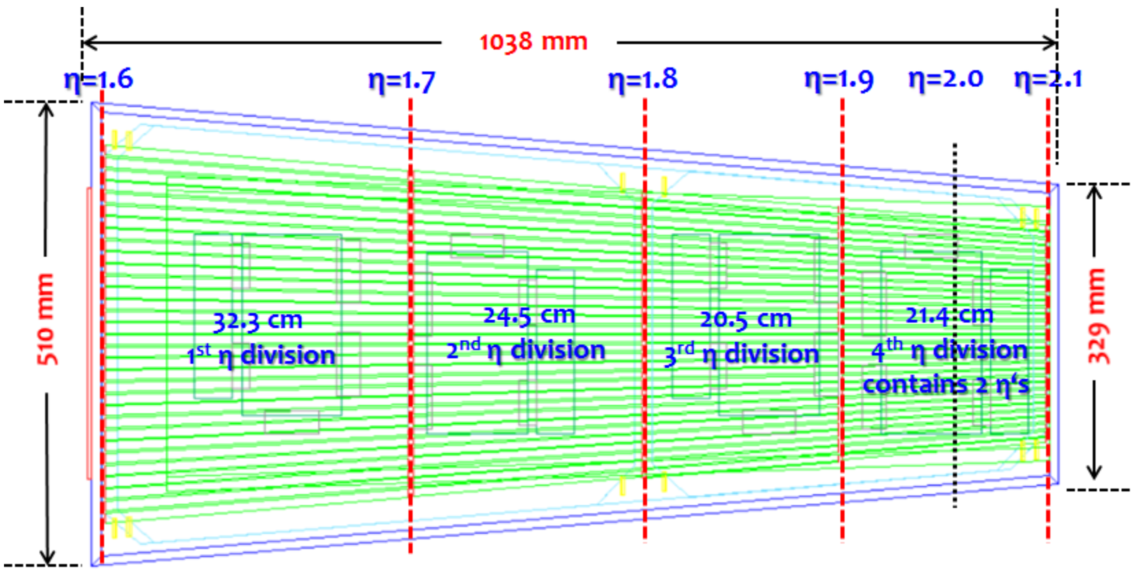
Have chosen the old RE1/1 RPC geometry (10°)

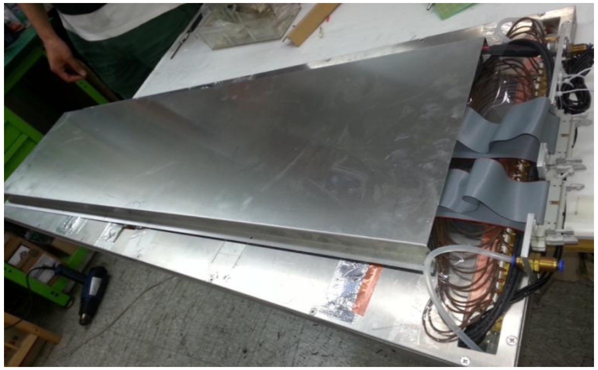
~ an half size of RE3/1 or RE4/1 (20°)

Strip lengths & pitches are close to RE3/1 (RE4/1).

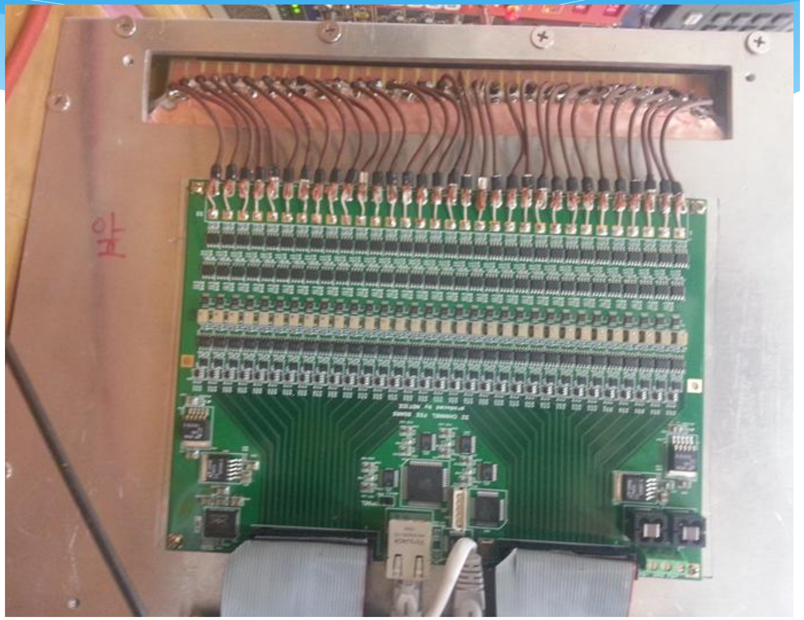
- ✓ **Narrow-pitch and short strips**
- ✓ Strip pitches: 7.5 ~ 13.3 mm
- ✓ Strip length: 32.3 cm (1.6~1.7) / 24.5 cm (1.7~1.8) / 20.5 cm (1.8~1.9) / 21.4 cm (1.9~2.1)







Two different type front-end electronics



1. 32-ch FEBs currently used for the CMS RPC operation

2. New 32-ch FEBs manufactured with commercial preamplifiers (voltage sensitive)

- ✓ Input impedance = 20 Ω
- ✓ Gain = 200 mV/mV
- ✓ Ethernet communication for adjusting thresholds
- ✓ LVDS output pulse width = 70 ns (fixed)
- ✓ Minimum sensitivity ~ 0.1 mV (~ 20 fC)
- ✓ Time resolution ~ 200 ps

For double-gap RPCs,

New FEBs	CMS RPC FEBs
Th = 1.0 mV	Th ~ 180 fC
Th = 0.75 mV	Th ~ 135 fC
Th = 0.60 mV	Th ~ 110 fC

⟷ **Equivalent**

For multi-gap (4-gap) RPCs,

New FEBs	CMS RPC FEBs
Th = 1.0 mV	Th ~ 120 fC
Th = 0.75 mV	Th ~ 90 fC
Th = 0.60 mV	Th ~ 70 fC

⟷ **Equivalent**

2. Test of the prototype RPCs at KODEL and GIF++/CERN

200-mCi ^{137}Cs at KODEL/Korea University.

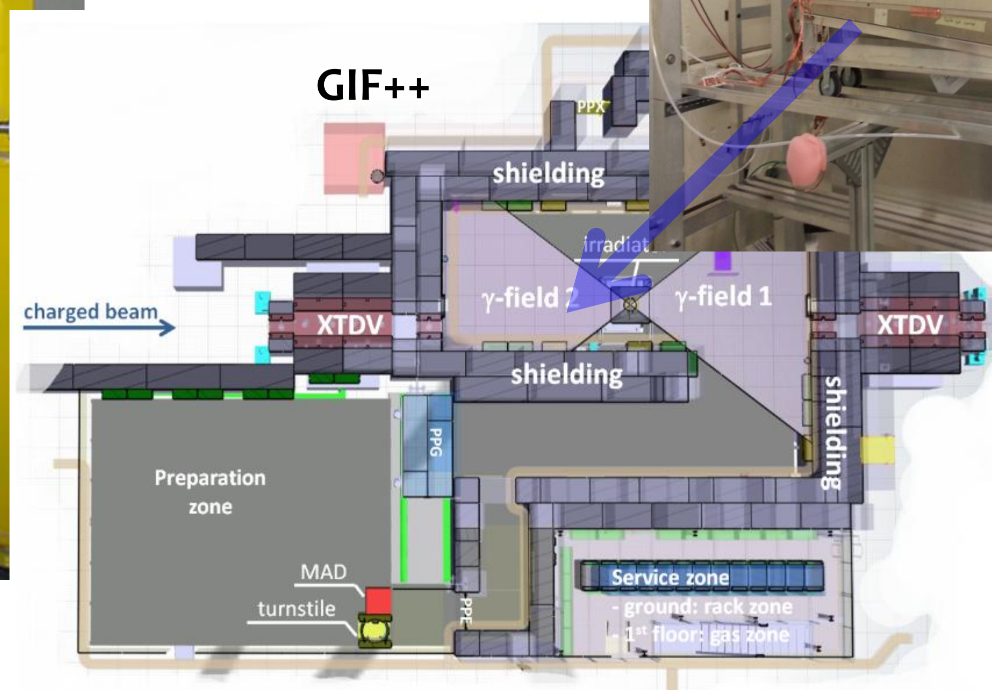
Current activity = 5.55 GBq

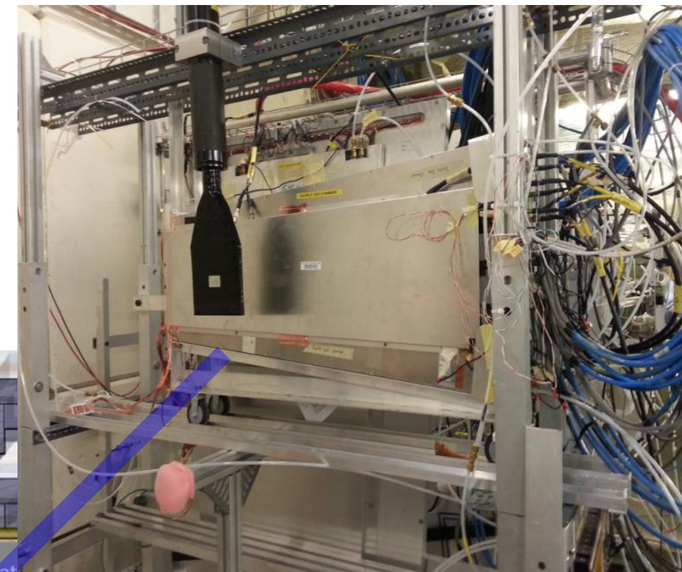
Maximum γ rate at 37 cm ~ 1.4 kHz cm^{-2}

GIF++ installed at H4 beam line

Activity = 1.4 TBq (^{137}Cs)

Maximum γ rate at the test position ~ 1.5 kHz cm^{-2}





Double-gap RPC (cosmic muons at KODEL)

Gas : 95.2% TFE + 4.5% iC_4H_{10} + 0.3% SF_6 + water vapor (0.3% in mass ratio)

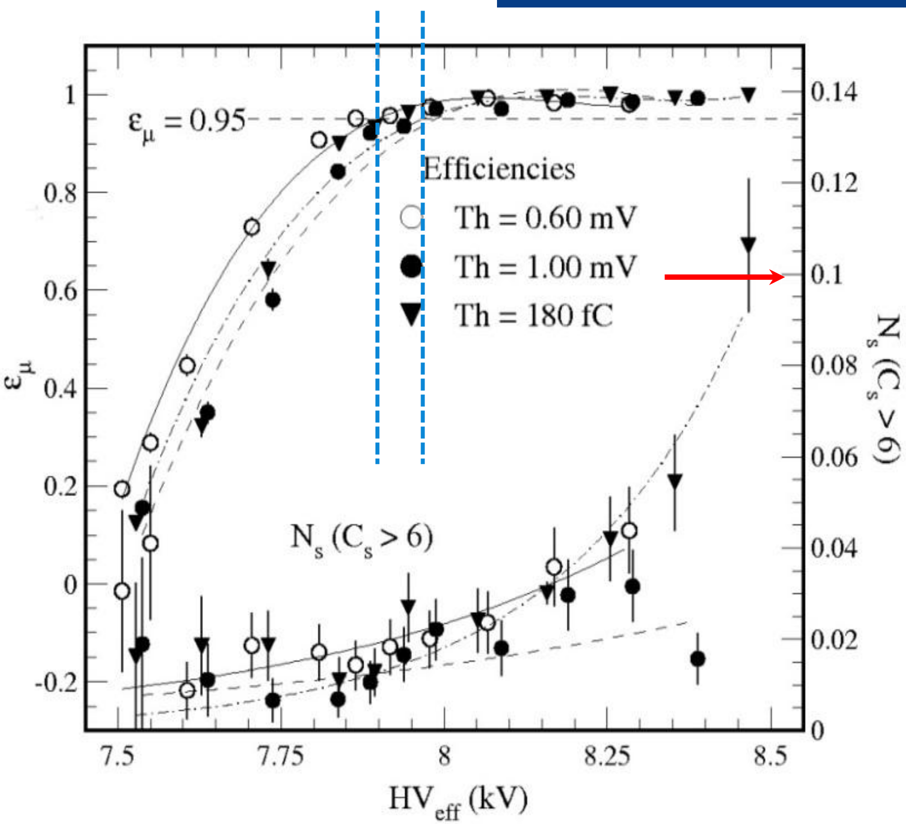
Realized a strong strip-pitch dependence of the RPC data

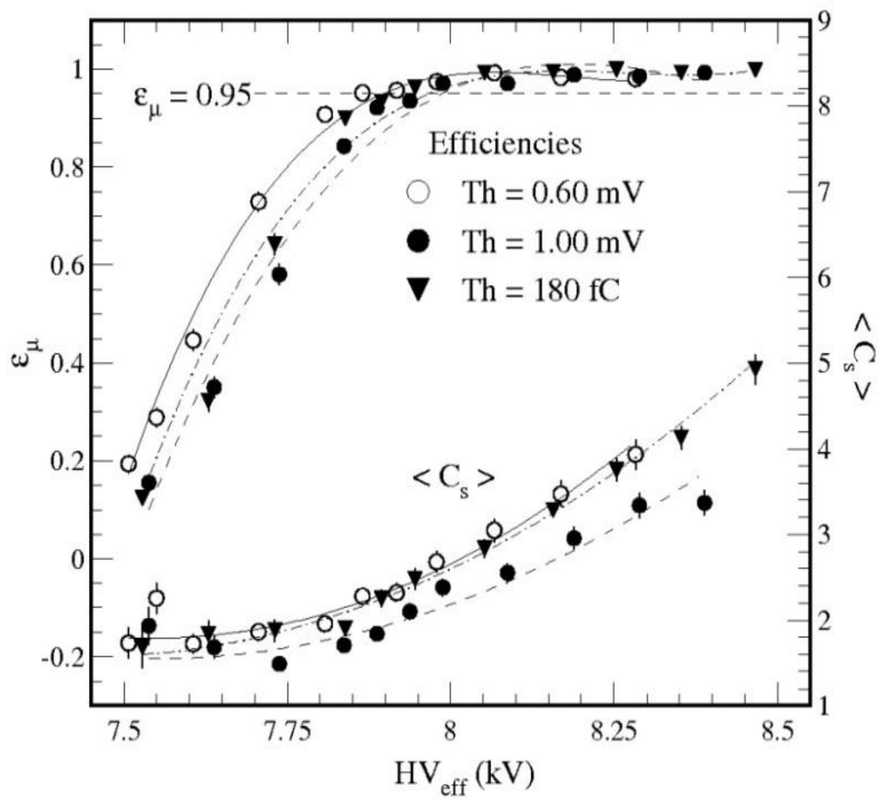
Checked threshold dependences of efficiencies & mean cluster sizes
The difference in HVs yielding 95-% efficiencies at Th = 0.6 mV and 1.0 mV (or ~ 180 fC) ~ 70 V.
But, threshold dependences of C_s and N_s are much larger.

70 V

1^{st} η region (mean strip pitch ~ 12 mm)

Usable range defined by ε >0.95 & N_s(C_s>6 < 10%)





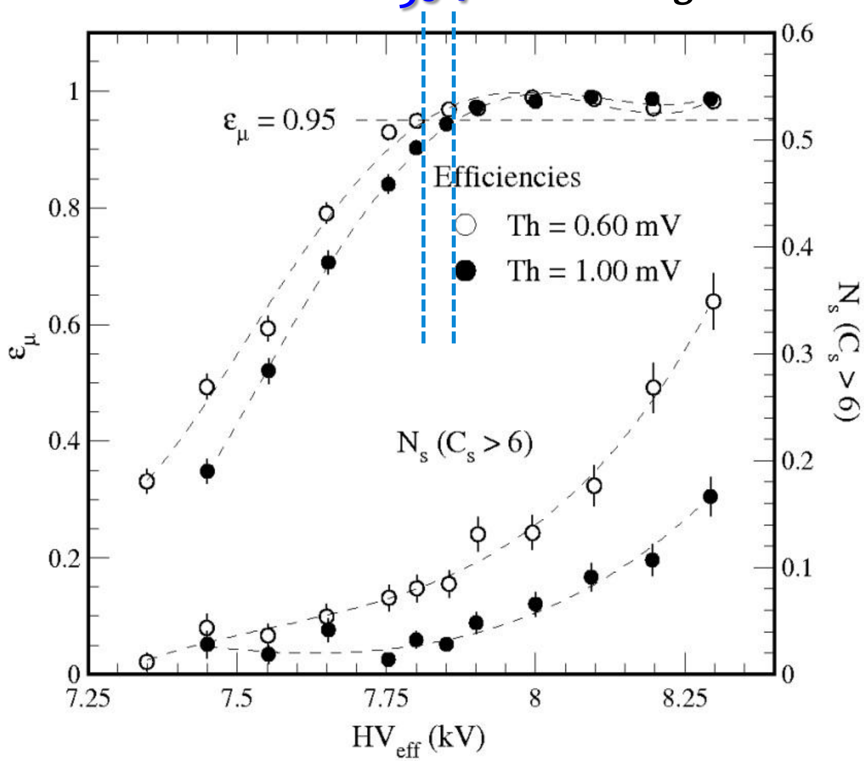
Realized that the threshold dependences of C_s and N_s are more severe for narrower strips.

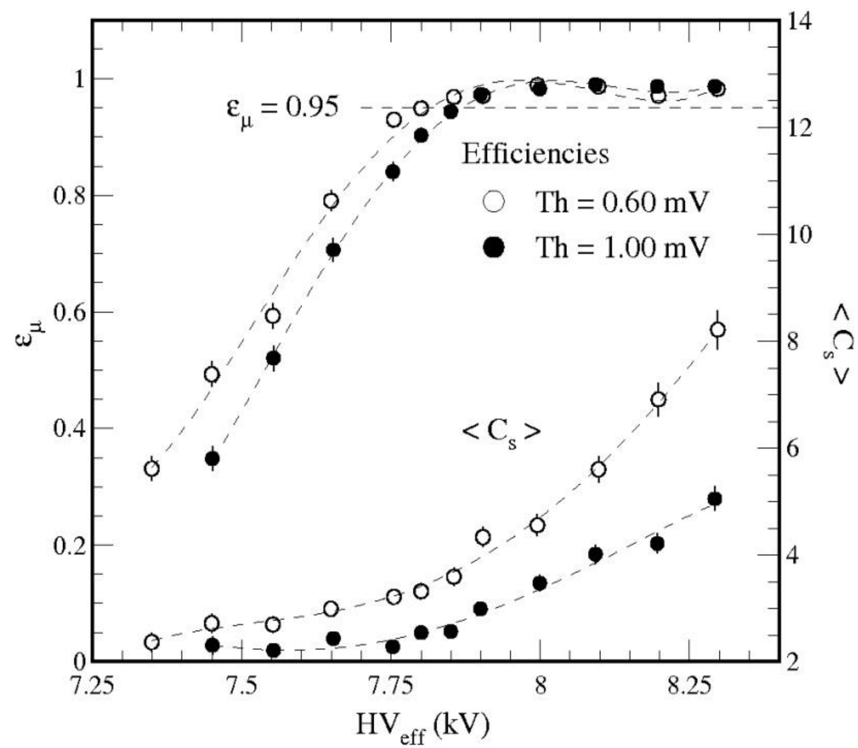
→ **Needs proper terminations with the matched strip impedance in FEBs.**

Or, needs fine tuning of threshold values to adapt various strip pitches.

3rd η region (mean strip pitch ~ 8.5 mm)

50 V **Usable range defined by ε >0.95 & N_s(C_s>6 < 10%)**





Multi-gap (4-gap) RPC (cosmic muons at KODEL)

Gas : 95.2% TFE + 4.5% iC_4H_{10} + 0.3% SF_6 + water vapor (0.3% in mass ratio)

Less strong threshold dependence of efficiencies & mean cluster sizes

Measured the muon data only with the new FEBs.

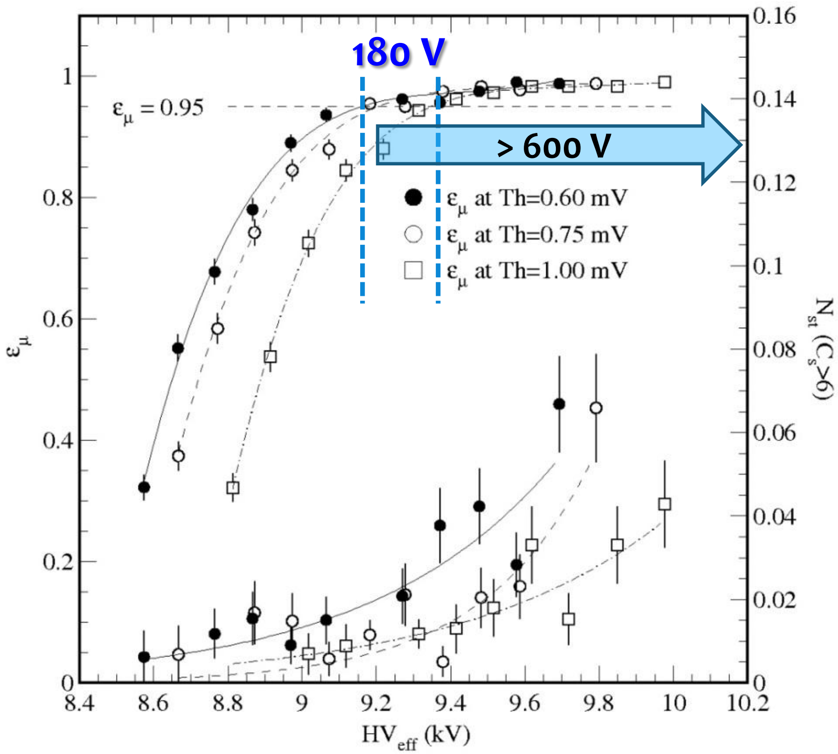
The difference in HVs yielding 95-% efficiencies measured at Th = 0.6 mV and 1.0 mV **~ 200 V.**

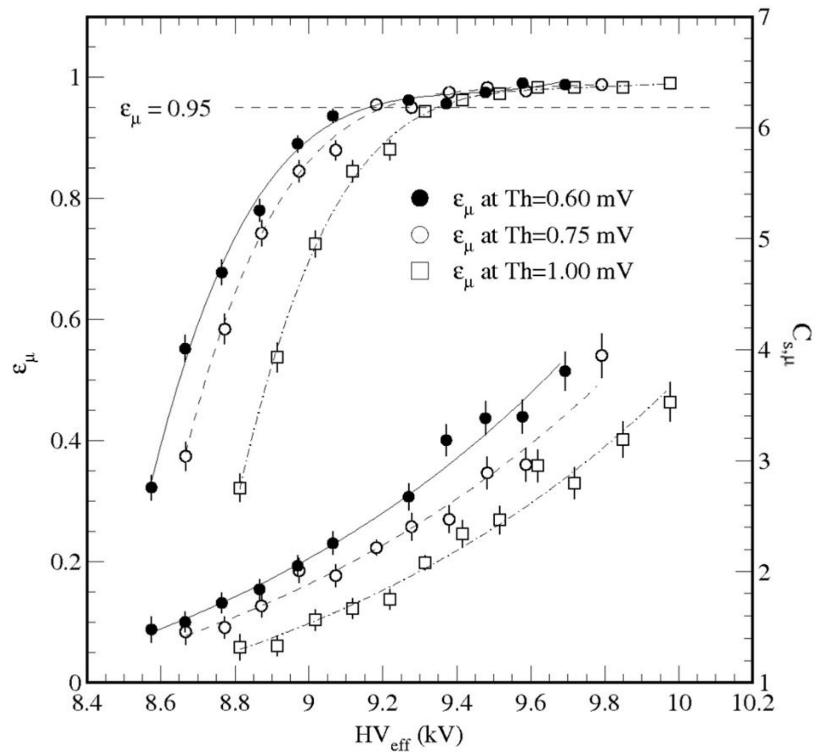
✓ The usable size of the efficiency plateau is **> 600 V** even for the data measured at **0.6 mV.**

→ Better to lower the digitization threshold to lower the gain of signals.

Usable range defined by ε >0.95 & $N_s(C_s>6 < 10\%)$

1st η region (mean strip pitch ~ 12 mm)

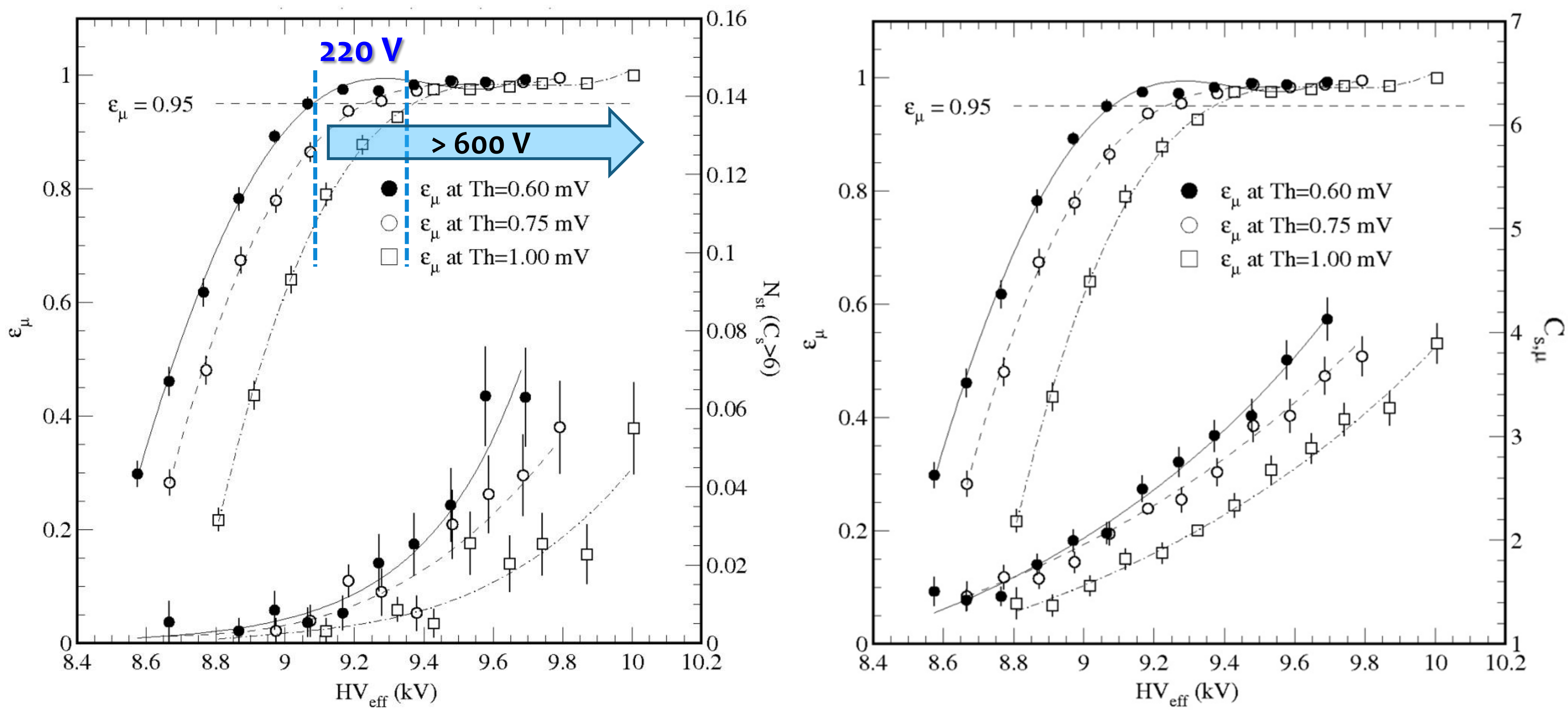




Multi-gap RPCs are less sensitive both to threshold and strip pitch

3rd η region (mean strip pitch ~ 8.5 mm)

Usable range defined by ε >0.95 & $N_s(C_s>6 < 10\%)$



Double-gap and Multi-gap (4-gap) RPCs tested with H4 beams at GIF++

Threshold dependence of efficiencies (muon beam only)

3rd η region (mean strip pitch ~ 8.5 mm)

Reconstructed of strip-hit clusters and applied proper cuts:

Time + Geometry + Beam area

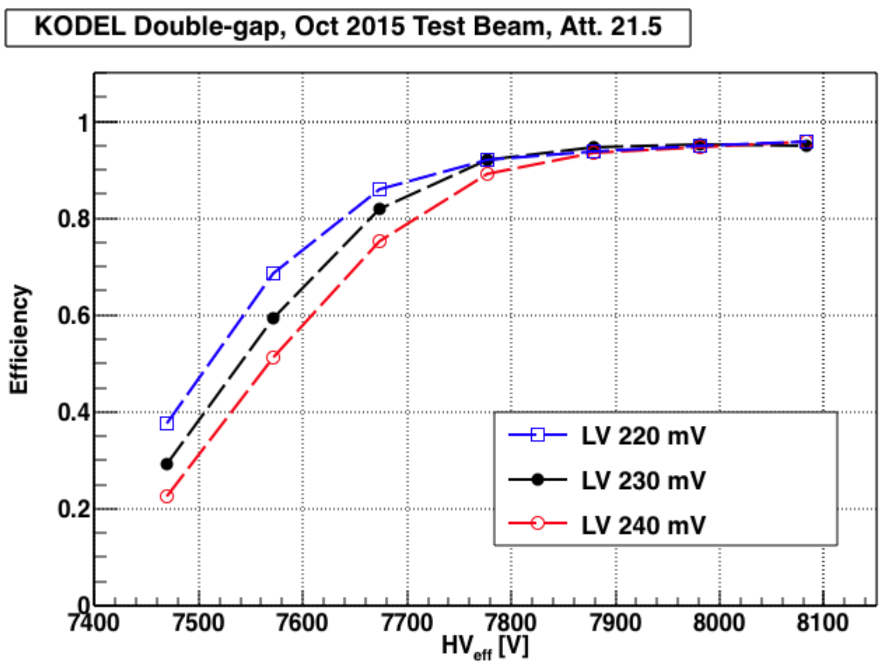
Double-gap RPC: Difference in HVs yielding 95-% efficiencies at Th = 170 and 240 fC **~ 70 V.**

Multi-gap RPC: Difference in HVs yielding 95-% efficiencies at Th = 170 and 240 fC **~ 140 V.**

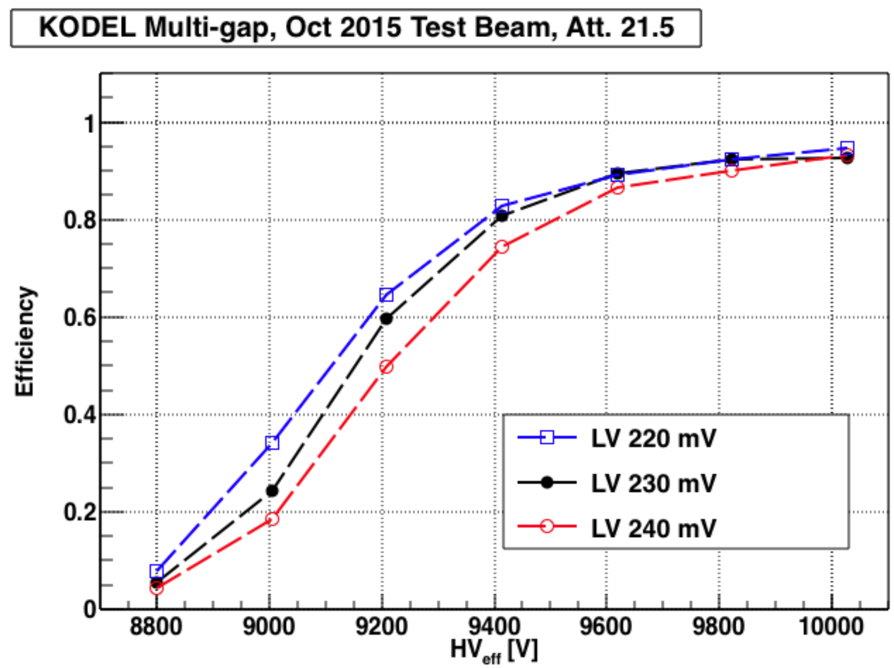
Thresholds for CMS RPC FEE

LV 220 mv ⇔ 170 fC
LV 230 mv ⇔ 190 fC
LV 240 mv ⇔ 240 fC

Double-gap RPC



Multi-gap RPC



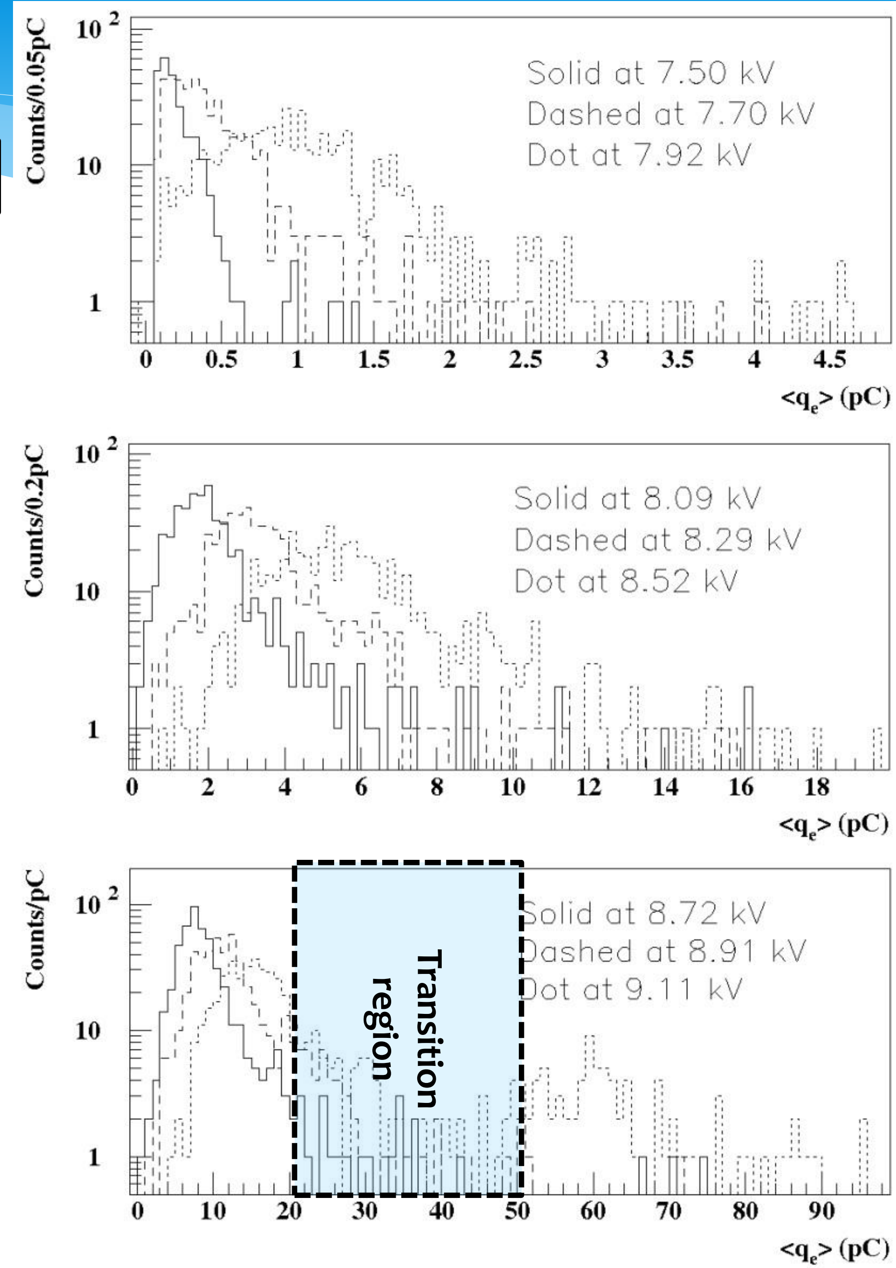
Charge spectra (using FADCs)

To understand the dynamic ranges of operation

- Gas = 95.1% TFE + 4.5% iC_4H_{10} + 0.4% SF_6
- Strip pitch = 12.0 mm (mid of 1st η section)
- Maximum time to measured = 320 ns
- ADC charges calibrated using a pulse generator

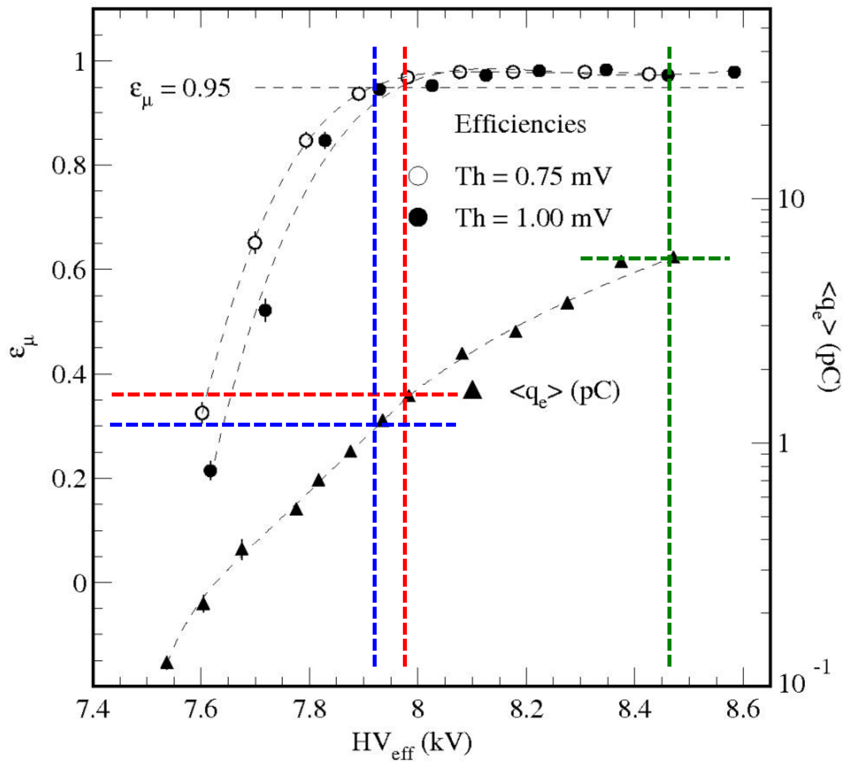
Double-RPC RPCs

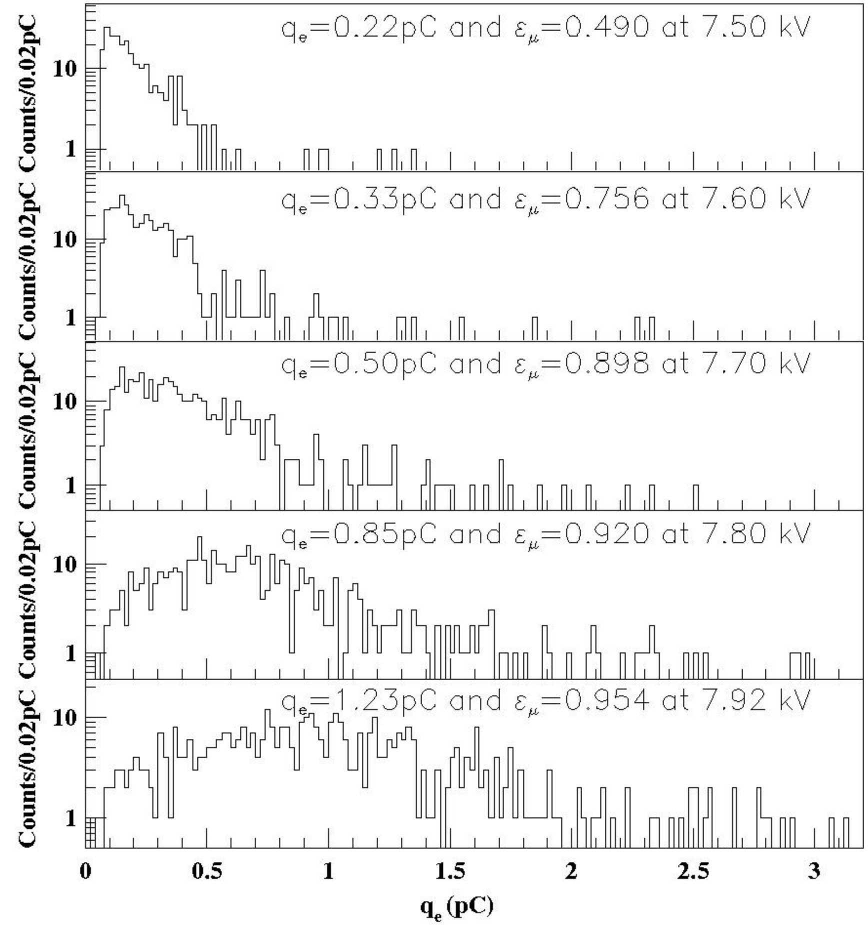
- The streamer probability N_s was defined as q_e > 20 pC (in the TDC data, C_s > 6)
- Transition region between avalanche and streamer regions lying in **$20\ pC < q_e < 50\ pC$.**



Double-gap RPCs

- The exponential growth of the pickup charges **becomes less stiffer near $\langle q_e \rangle \sim 1$ pC.**
  → **Can expect that a wider usable range for the operation obtained with Th = 180 fC (or 1.0 mV).**
- As lowering the threshold, the usable plateau range is getting narrower.
  → **Found no advantage of choosing lower thresholds.**





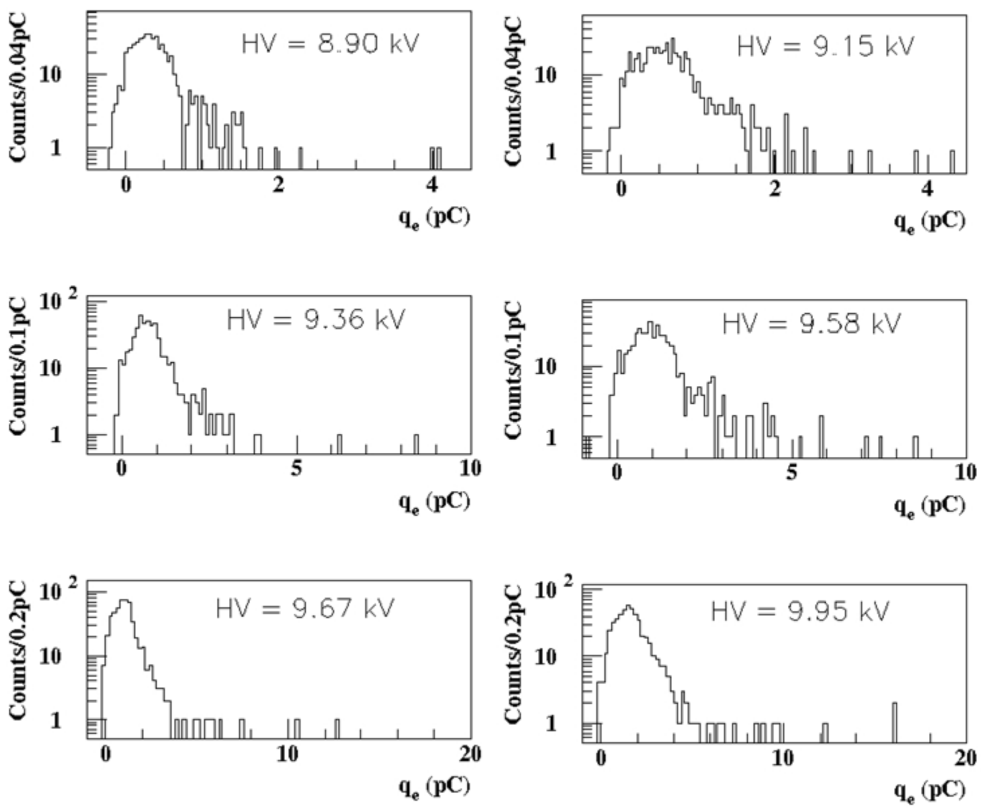
$\langle q_e \rangle \sim 1.65$ pC at $\varepsilon_\mu = 0.95$ (Th = 1.0 mV)
$\langle q_e \rangle \sim 1.30$ pC at $\varepsilon_\mu = 0.95$ (Th = 0.6 mV)
$\langle q_e \rangle \sim 5.5$ pC: limit of avalanche mode

Charge spectra (using FADCs) for Multi-gap RPCs

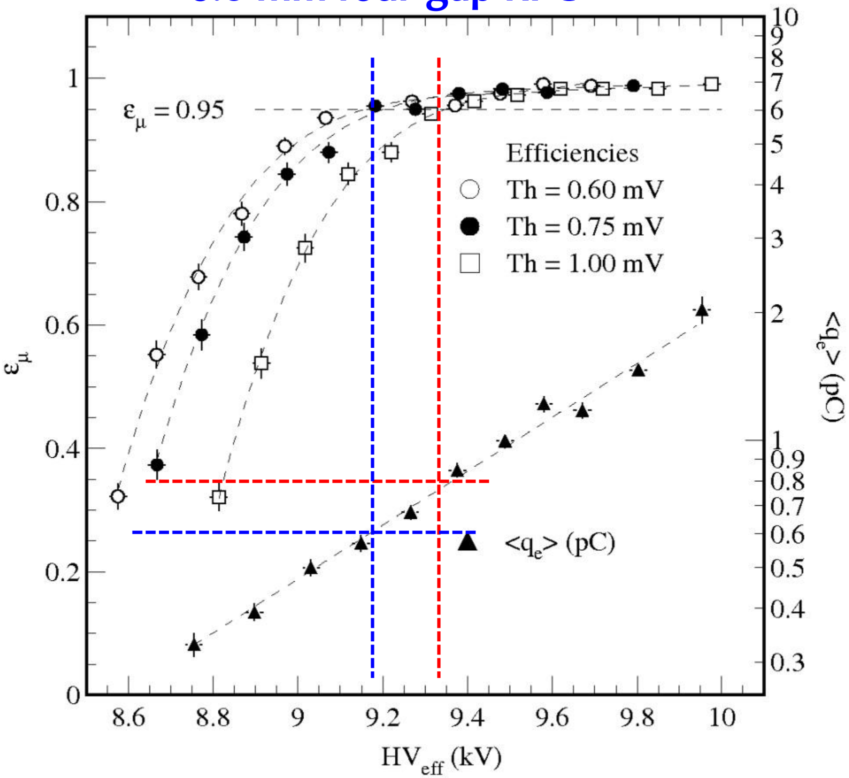
The slope of the exponential growth is saturated even **at very low <q_e>.**

This is the reason why the wide usable plateau range was obtained even **with Th = 0.6 mV.**

→ Better to adopt lower thresholds to enhance the detector sensitivity to **maximize the rate capability** and while to **minimize aging** due to high-rate beam background.



0.8-mm four-gap RPC



<q_e> ~ 780 fC at ε_μ = 0.95 (Th = 1.0 mV)

<q_e> ~ 600 fC at ε_μ = 0.95 (Th = 0.6 mV)

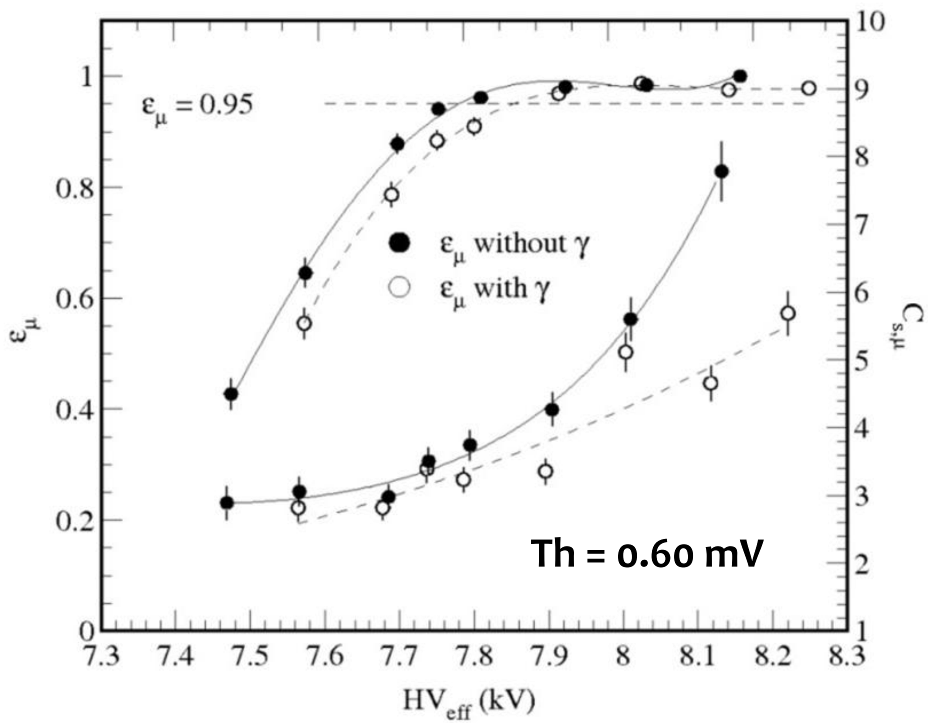
Influence of gamma rates measured at KODEL (5.55 GBq ^{137}Cs)

- ✓ Tagged cosmic muons with/without presence of gamma background
- ✓ Installed each testing RPC at 37 cm from source → **Gamma flux = 0.32 MHz cm^{-2}**

Irradiation area ~ 1000 cm^{-2} → max. γ rates in 2-gap or 4-gap RPCs ~ 1.4 kHz cm^{-2}

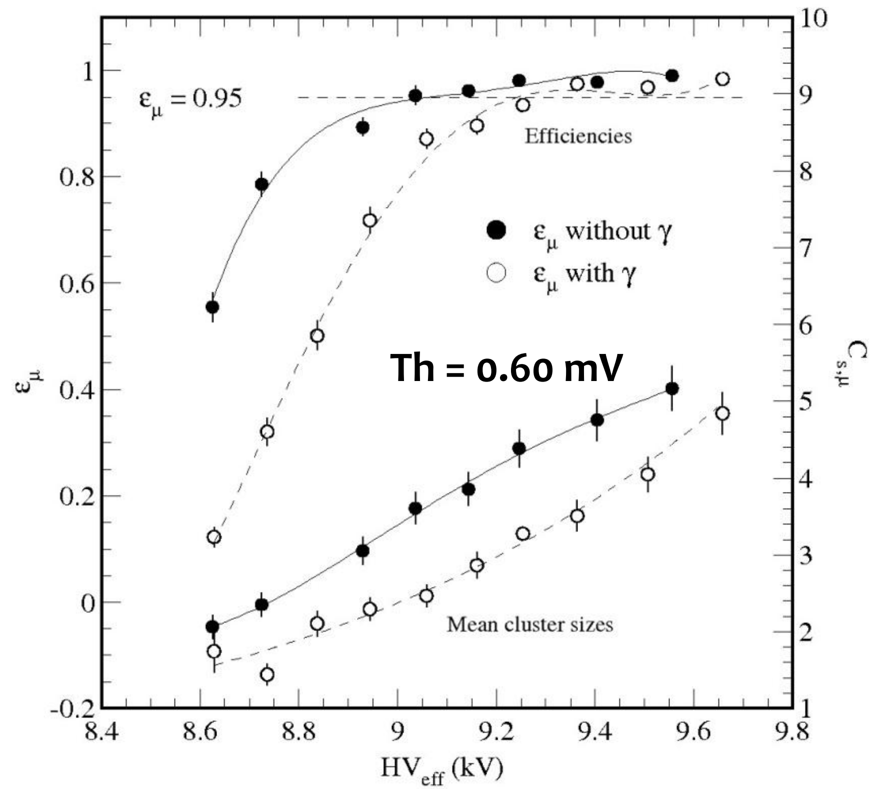
Double-gap RPC

Shift @ ε=0.95 in HV due to the γ background **~ 70 V**
(yielding ~ 1 kHz cm^{-2} at the mid of the plateau)
→ Rate capability >> 1 kHz cm^{-2}



Multi-gap RPC

Shift @ ε=0.95 in HV due to γ **~ 200 V**
(larger than the 2-gap RPC case)
But, confirmed the rate capability ~ 5 kHz cm^{-2}



γ rates and currents (KODEL)

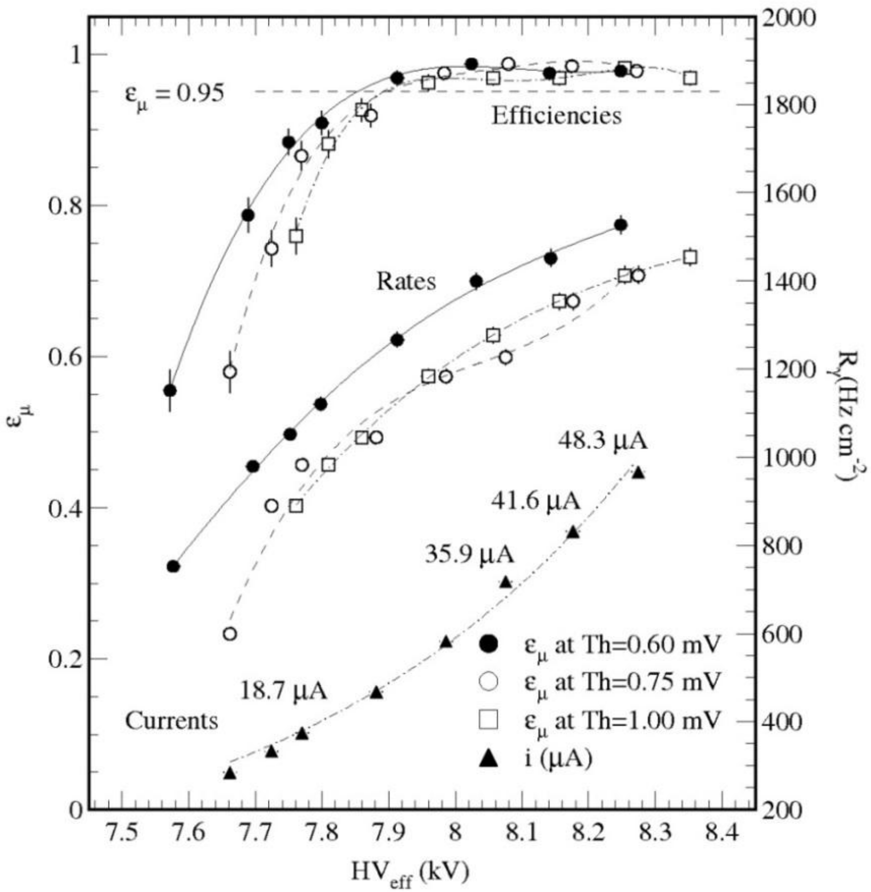
Double-gap RPC

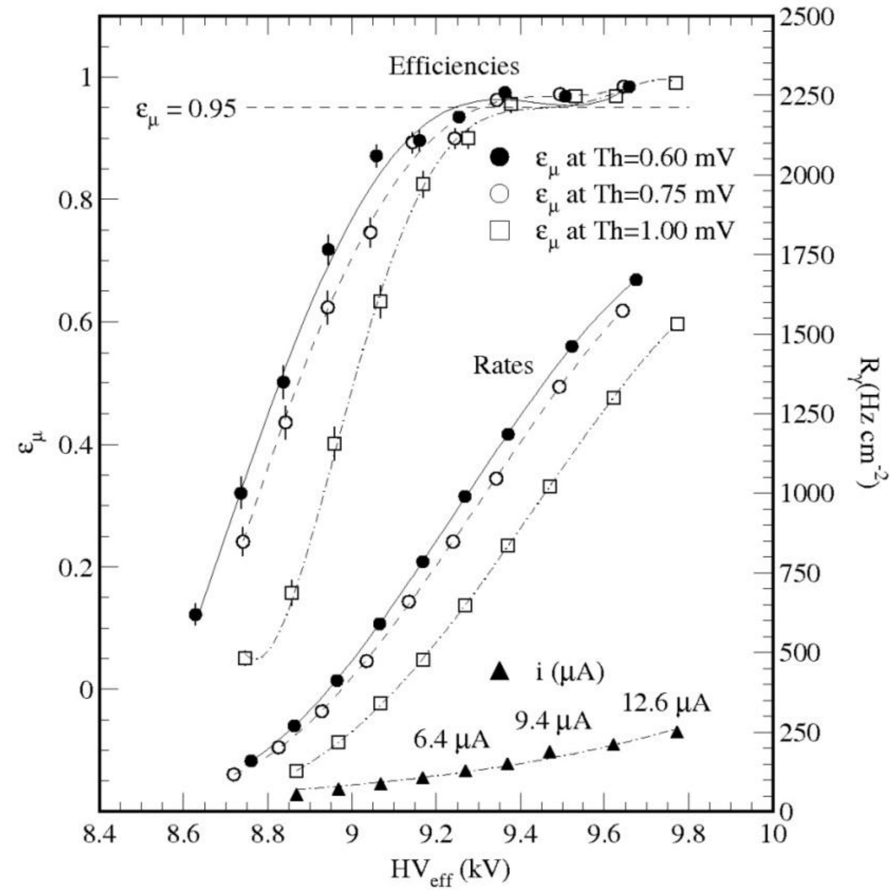
- ✓ Detector efficiency for 662-keV γ ~ 60% of Q.E. (by GEANT) at **$HV_{\varepsilon=0.95}$ + 150 V.**
- ✓ <Q $_{e,\gamma}$> ~ 25 pC at **$HV_{\varepsilon=0.95}$ + 150 V.**

Multi-gap RPC

- ✓ Detector efficiency for 662-keV γ ~ 40% of Q. E. (by GEANT) at **$HV_{\varepsilon=0.95}$ + 200 V.**
- ✓ <Q $_{e,\gamma}$> ~ 6.5 pC at **$HV_{\varepsilon=0.95}$ + 200 V.**

→ **~ 4 times smaller than the 2-gap RPC case**



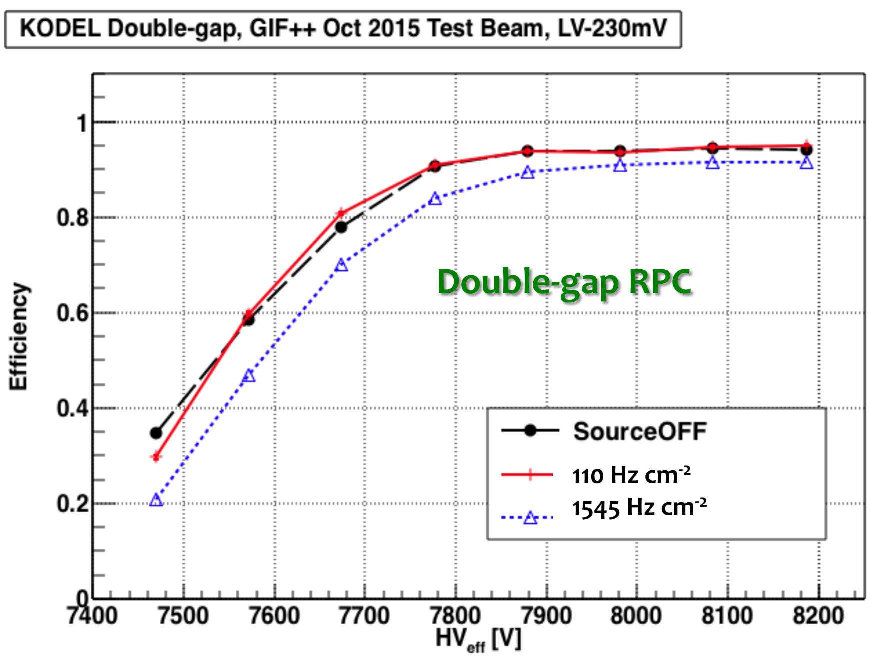


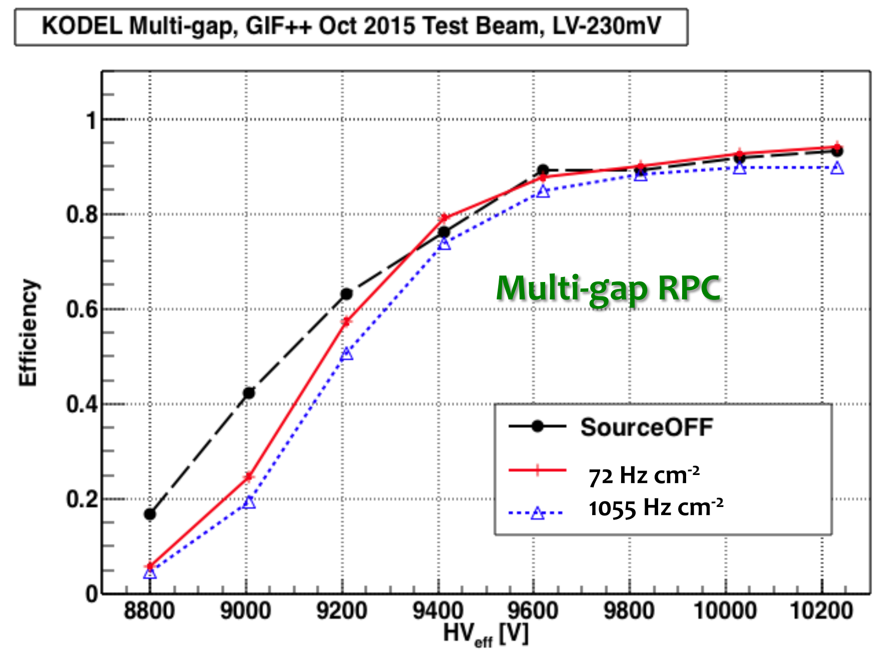
Rate dependence of efficiencies measured at GIF++ (1.4 TBq ^{137} Cs)

Shift @ ε=0.95 in HV due to γ background **~ 70 V** for the double-gap RPC

Shift @ ε=0.95 in HV due to γ background **~ 100 V** for the multi-gap RPC

Efficiencies (just subtracted for gamma background)





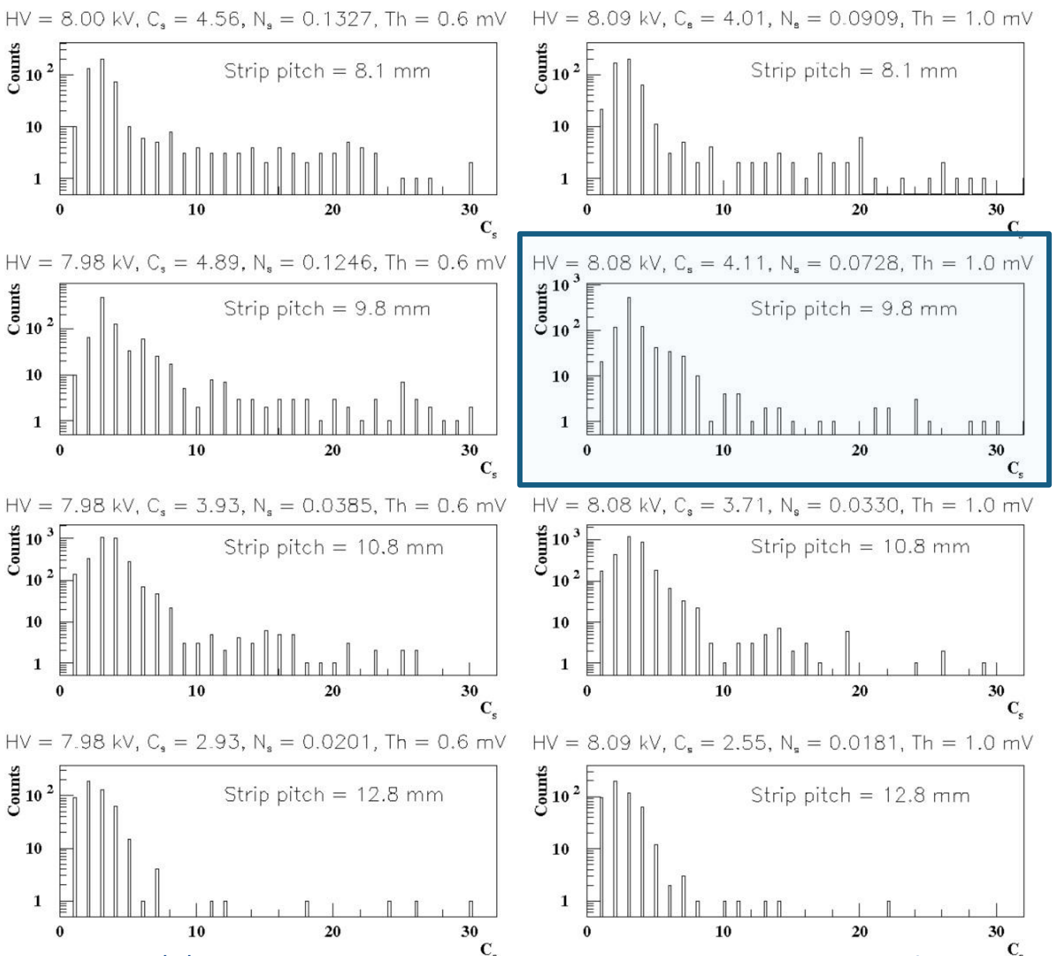
Double-gap RPCs: Long tails in C_s distributions (KODEL and GIF++)

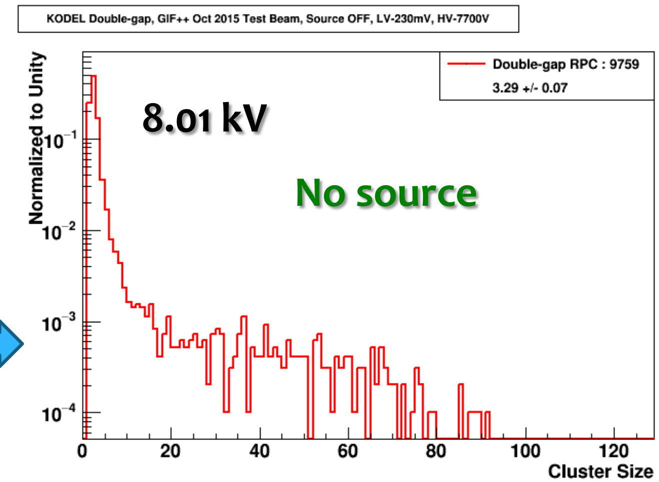
- ✓ Stronger capacitive coupling due to **no strip termination and impedance mismatching.**
- ✓ The trend is more severe when measured at the low threshold and with narrower-pitch strips

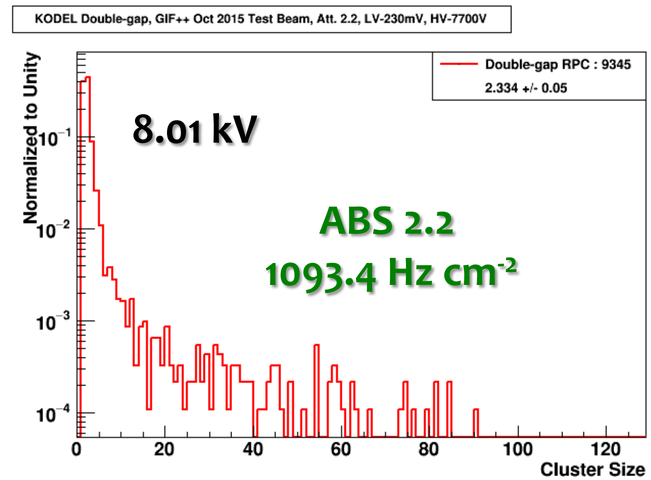
→ Needs proper terminations with the matched strip impedance in FEBs.

Fixed input impedance at CMS-RPC FEBs = 15 Ω

Th = 0.6 mV **KODEL** **No source** **Th = 1.0 mV** **GIF++**



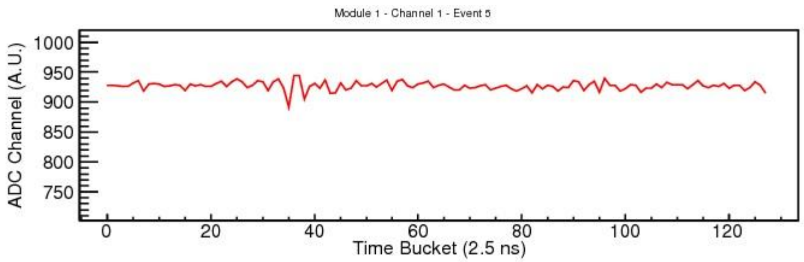


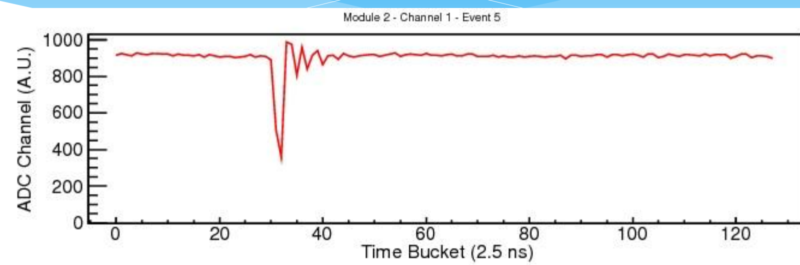


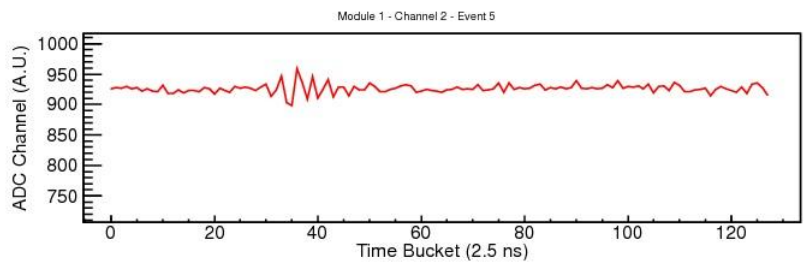
Strong capacitive couplings among narrow-pitch strips (measured FADCs)

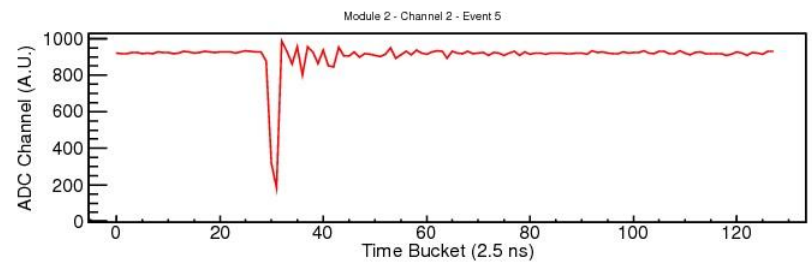
Muon pulses tagged at a region with strip pitch of ~ 11.0 mm

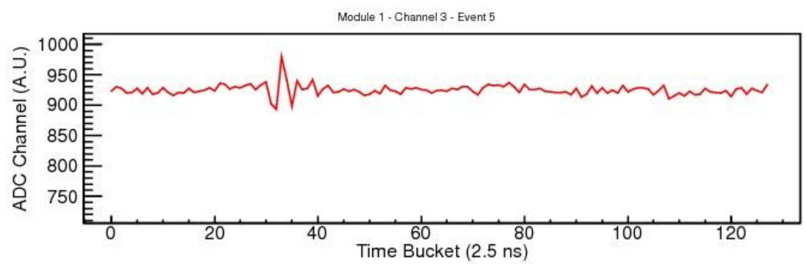
Cross talks ~ 15%

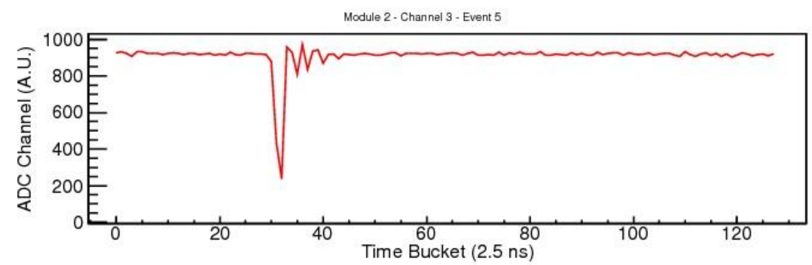


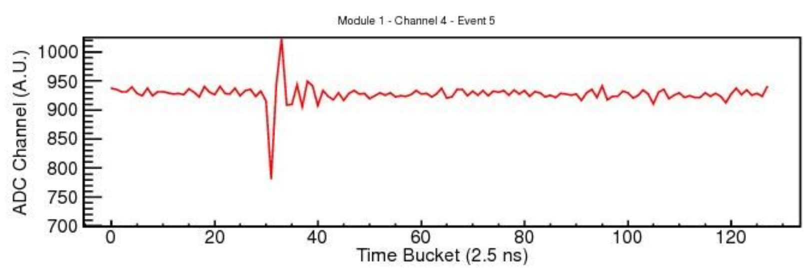


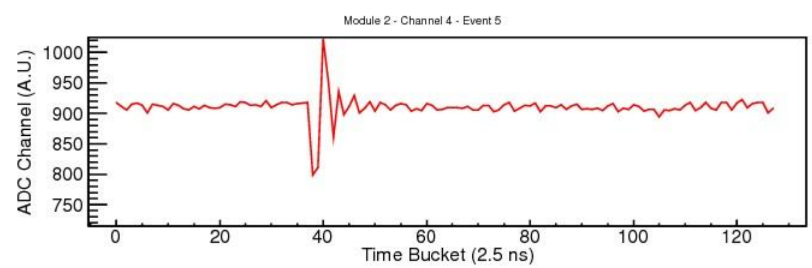




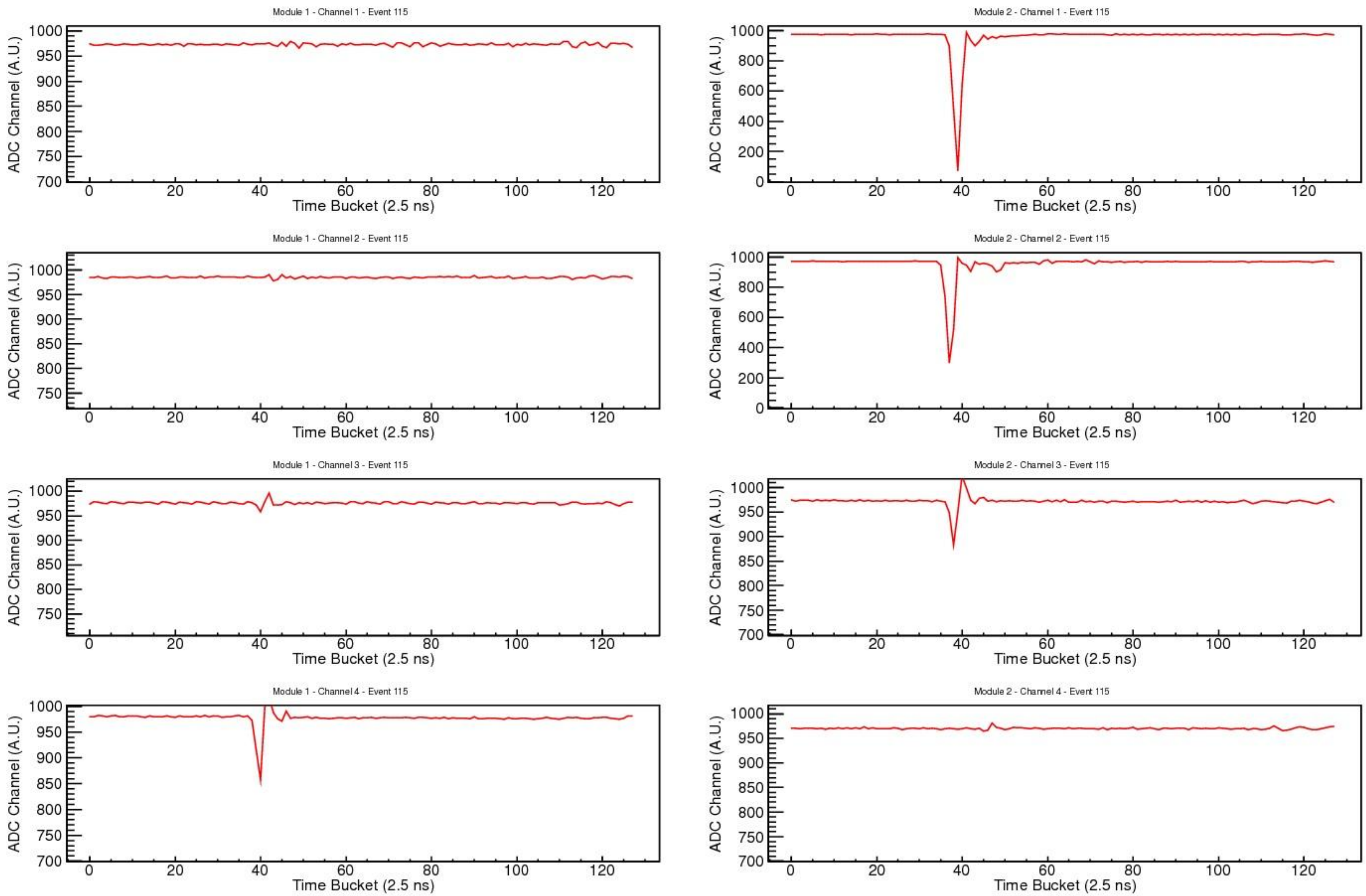








Muon signals of the same detector but with strip pitches of ~ 22.0 mm
Capacitive couplings are less severe with wider-pitched strips.

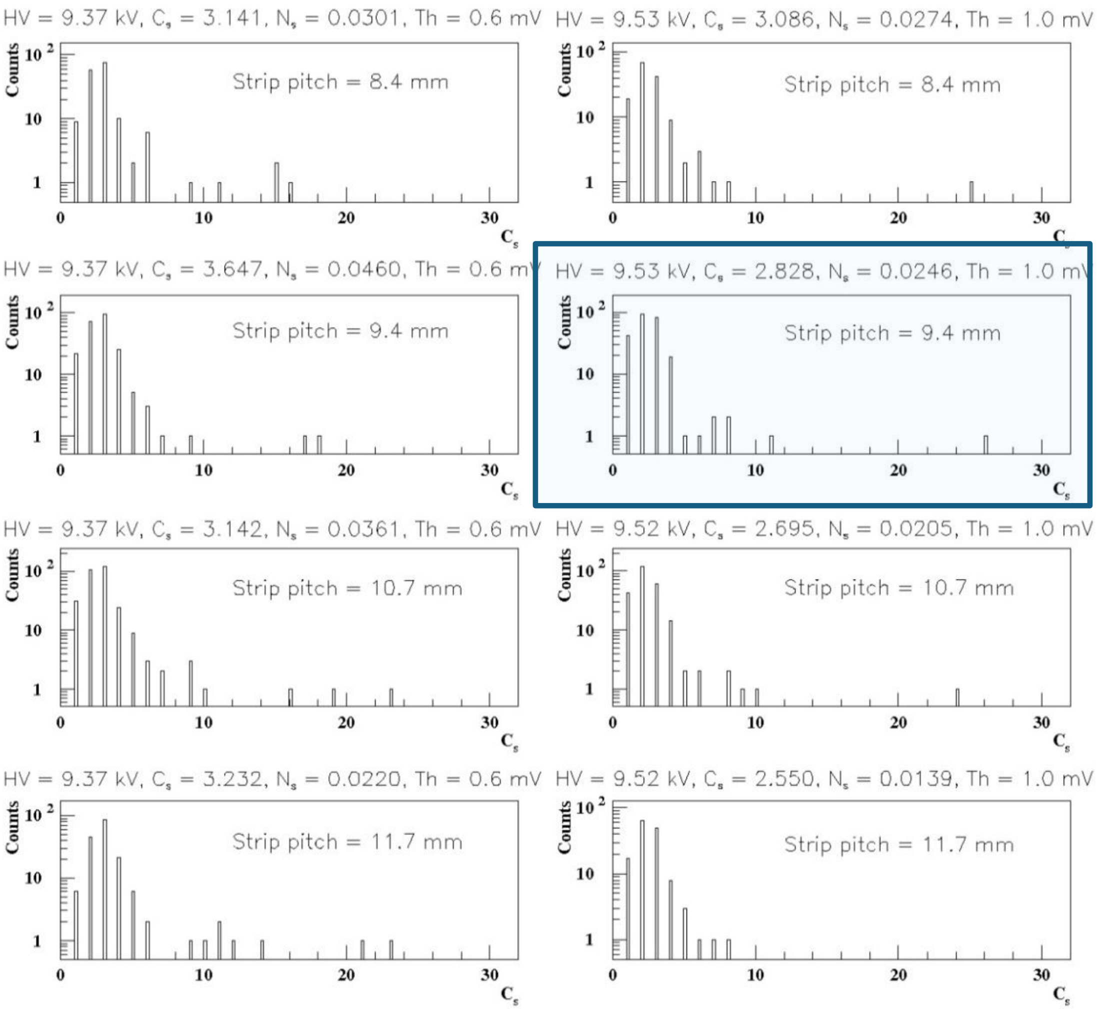


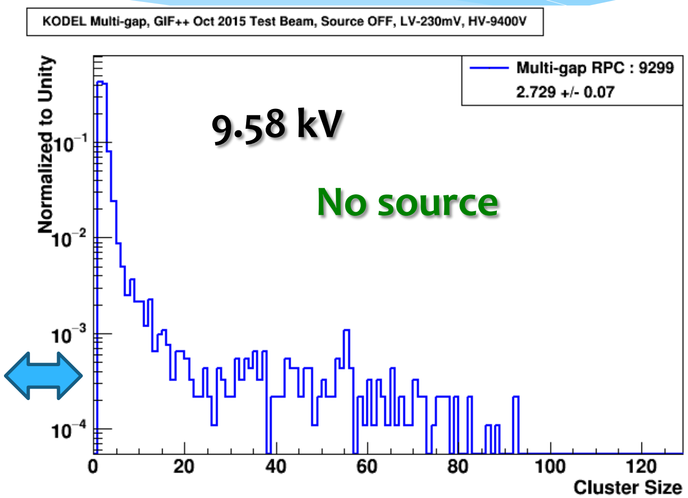
Multi-gap RPC: Tails in cluster-size distributions (KODEL & GIF++)

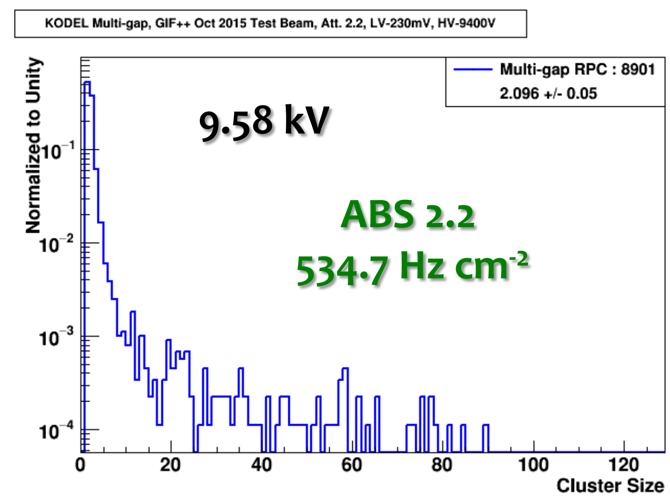
- ✓ The tails are less severe for multi-gap RPCs
- ✓ The threshold and pitch dependences are also lower.

Th = 0.6 mV **KODEL** **No source** **Th = 1.0 mV**

GIF++ **Fixed input impedance at CMS-RPC FEBs = 15 Ω**







3. Conclusions

Confirmed the detector performances for the two different type RPCs.

For 1.6-mm double-gap RPCs instead of 2.0-mm gaps

1. The operational **HV = 7.8 ~ 8.4 kV** with Th = 180 fC.
   → **~ 15% lower than the current CMS RPCs**
2. The higher threshold was preferred to suppress the large C_s measured at narrower-pitch strips.
   → **But, needs proper impedance-matched terminations, and (could be) optimization of geometrical factors (thicknesses of gaps and electrodes).**
3. Rate capability issues: shift ~ **50 V / (kHz cm^{-2})** in HV.
   → **Confirmed the rate capability >> 1 kHz cm^{-2}.**

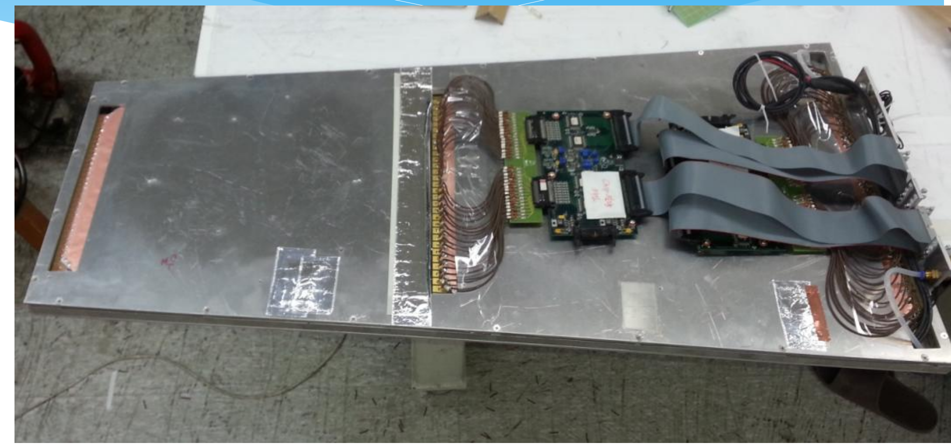
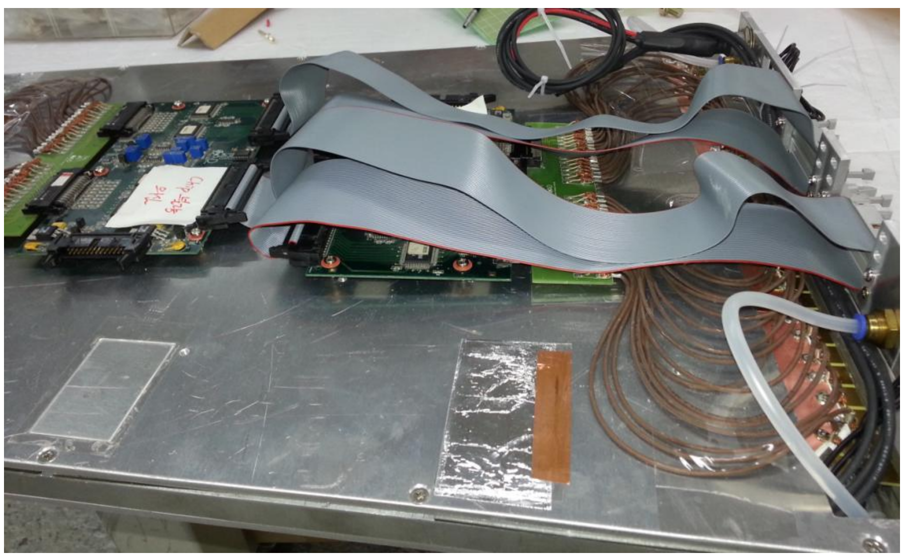
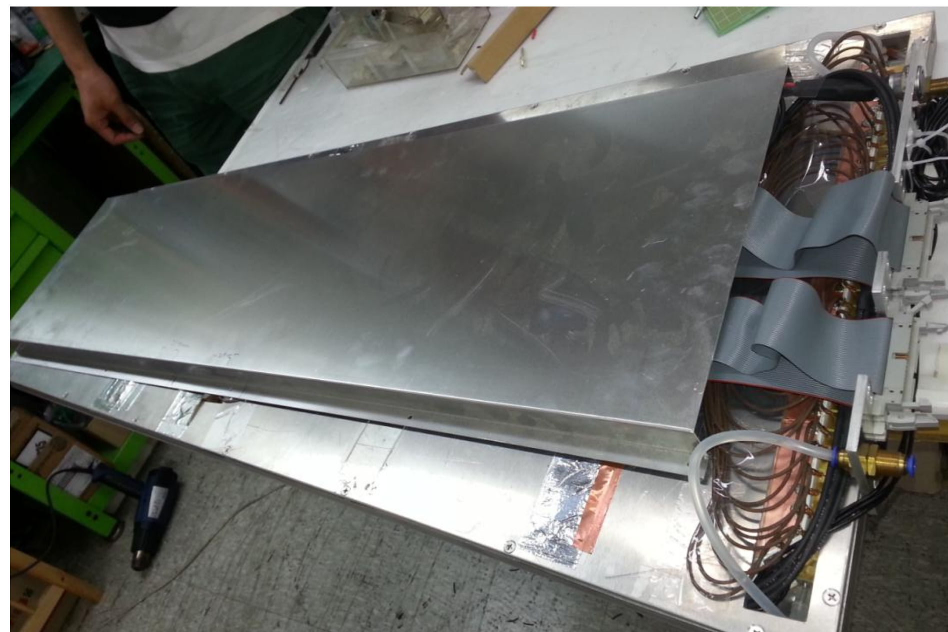
For 0.8-mm multi-gap(4-gap) RPCs

1. The operational **HV = 9.0 ~ 9.8 kV**
2. Lowering the threshold is more relevant compared to the 2-gap RPC case.
3. Rate capability issues:

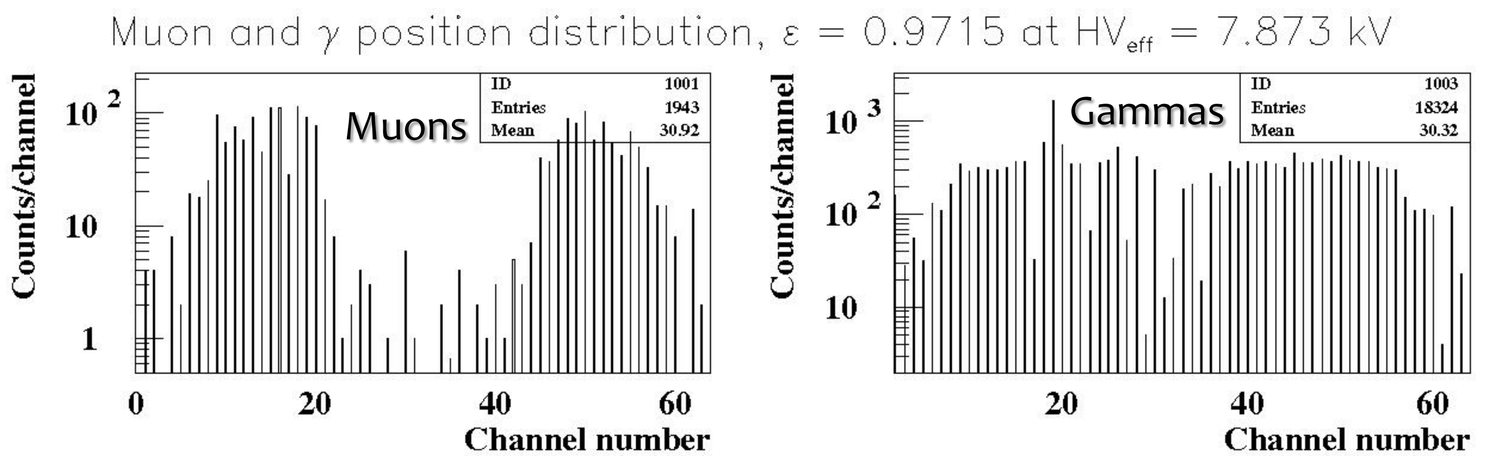
- ✓ Shift **~ 150 V / (kHz cm^{-2})** is larger than of the 2-gap RPC case **because of the floating electrodes.**
- ✓ But, rate capability **~ 5 kHz cm^{-2}** already confirmed in the previous R&D.
- ✓ Gamma induced current in the 4-gap RPC ~ factor 4 smaller than the double-gap RPC case.
  → **Better for aging.**

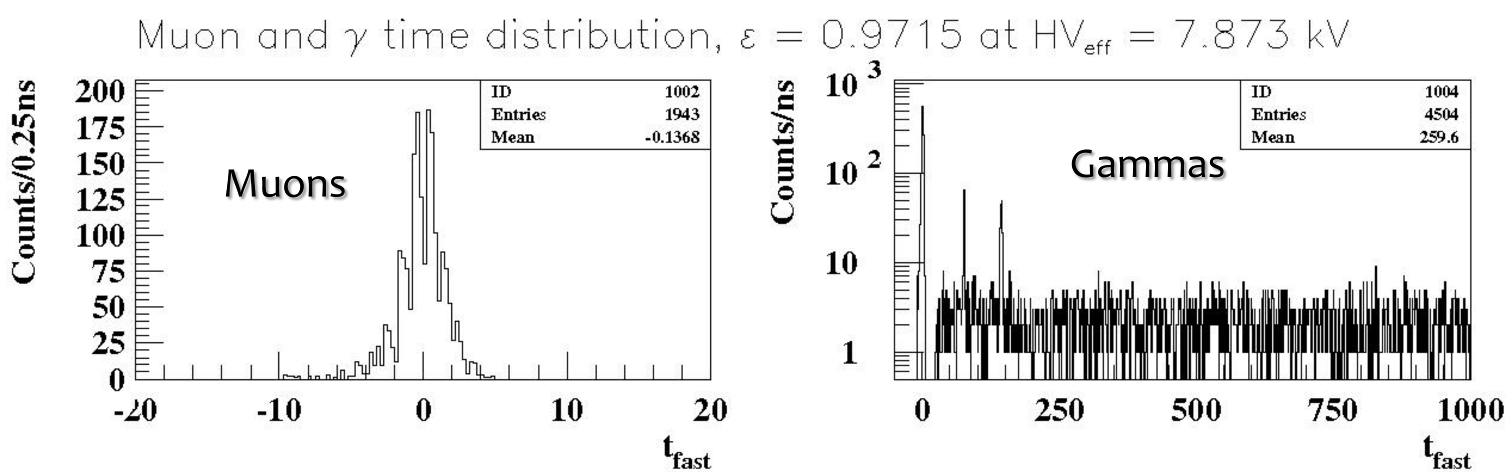
In the final conclusion, both types are good candidates !

Backups

Double-gap RPC





Gamma flux = 0.32 MHz cm^{-2} at 37 cm from the ^{137}Cs source measured at KODEL

1.6-mm double-gap RPC		
Threshold	γ rates (Hz cm^{-2}) (mid of plateau)	Current (μA) (Irradiated area =1000 cm^2)
0.60 mV	1398.8	33.01
0.75 mV	1319.0	35.02
1.00 mV	1277.0	39.11

0.8-mm multi-gap RPC		
Threshold	γ rates (Hz cm^{-2}) (mid of plateau)	Current (μA) (Irradiated area =1000 cm^2)
0.60 mV	1462.1	8.06
0.75 mV	1334.9	9.15
1.00 mV	1299.0	9.42

Strip pitch ~ 8.0 mm (η-section 3)

Measured at 0.6 mV (double-gap RPC)

HV_{eff}	ε	$<C_s>$	C_s=1,2,3	C_s=4,5,6	$C_s > 6$
7.67 kV	0.976	3.45	0.796	0.102	0.082
7.77 kV	0.980	3.86	0.771	0.139	0.090
7.87 kV	0.988	6.79	0.494	0.243	0.289
7.97 kV	0.988	8.40	0.324	0.300	0.377

Measured at 180 fC (Double-gap RPC)

HV_{eff}	ε	$<C_s>$	C_s=1,2,3	C_s=4,5,6	$C_s > 6$
7.92 kV	0.966	3.09	0.810	0.155	0.035
8.02 kV	0.985	3.68	0.790	0.190	0.030
8.13 kV	0.985	3.89	0.654	0.276	0.047
8.21 kV	0.996	4.58	0.580	0.369	0.055

The suppression of C_s due to the gamma background is stronger for the double-gap RPC.

Double-gap RPC

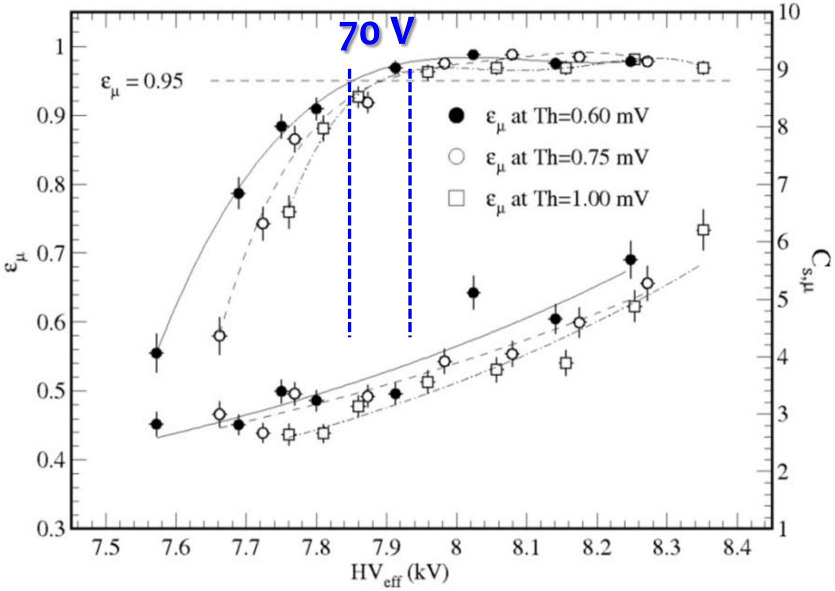
Shift @ ε=0.95 in HV due to raising the threshold from 0.6 to 1.0 mV **~ 70 V.**

Multi-gap RPC

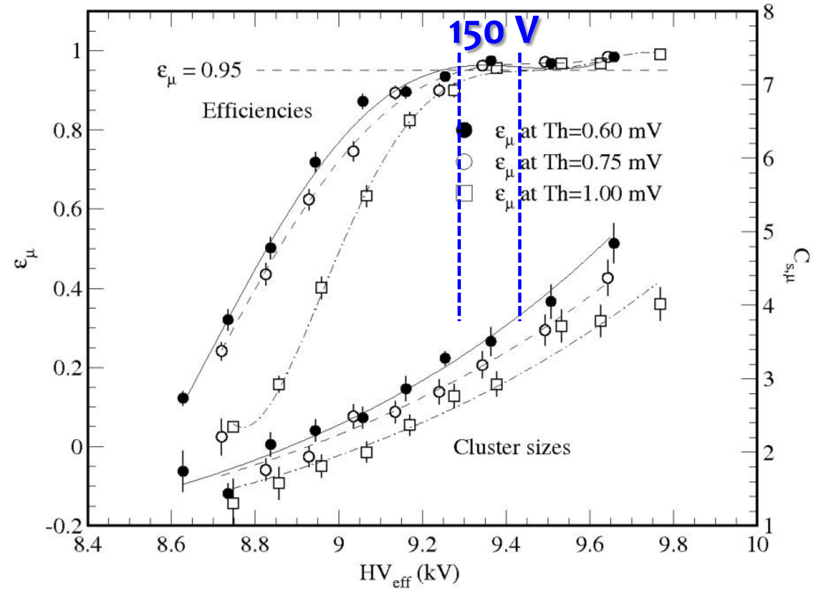
Shift @ ε=0.95 in HV due to raising the threshold from 0.6 to 1.0 mV **~ 150 V.**

Threshold dependence with presence of gamma background

Double-gap RPC

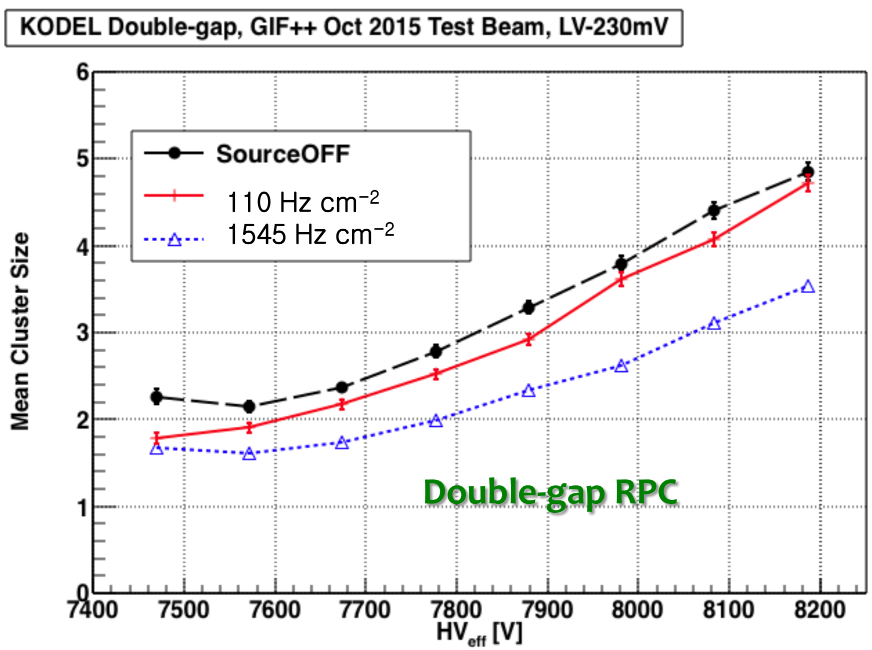


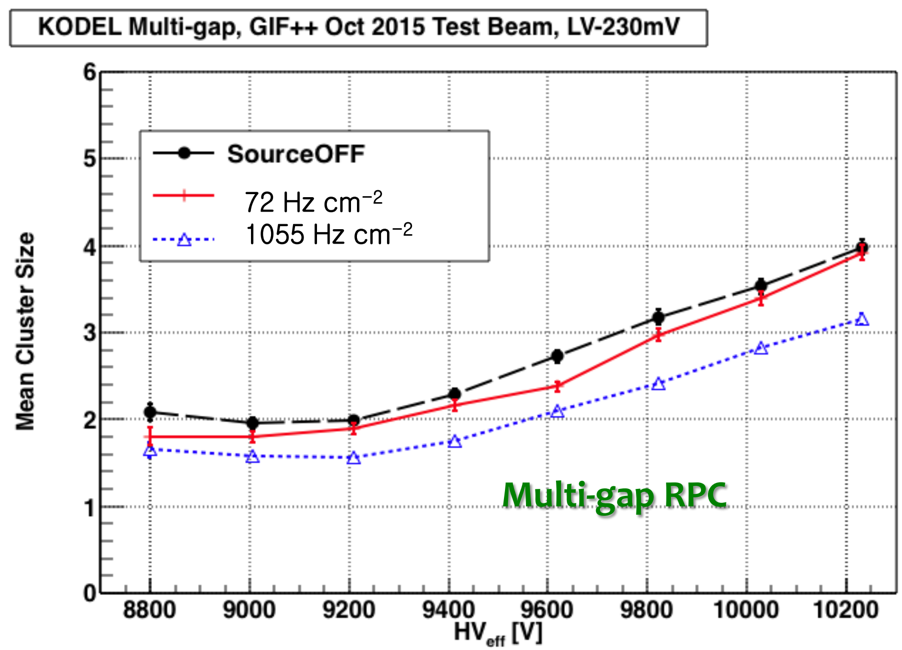
Multi-gap RPC



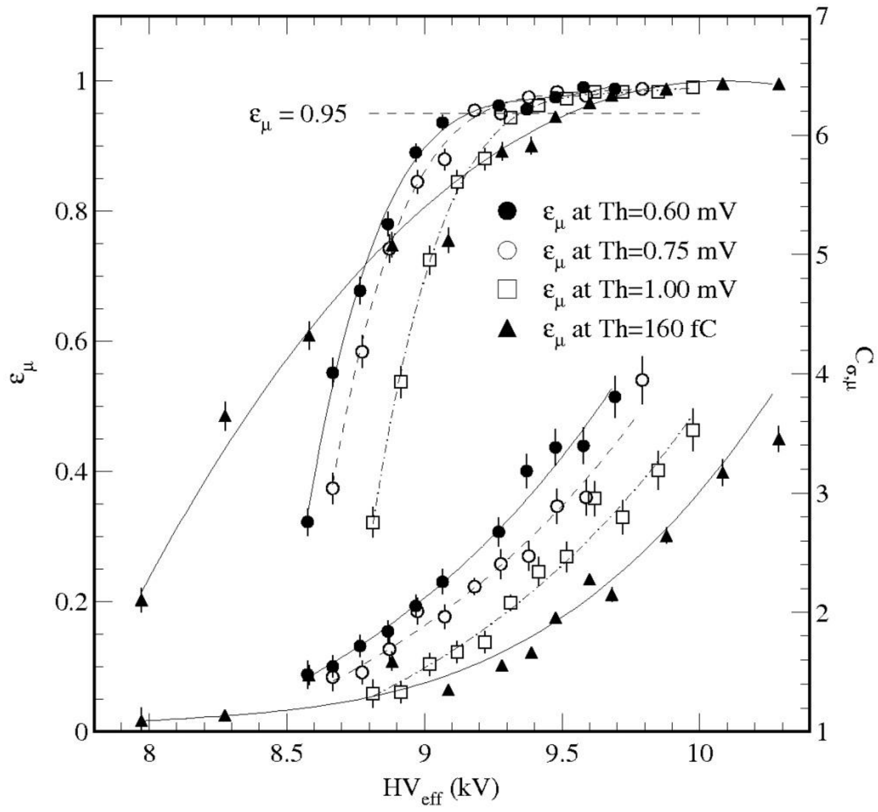
The suppression of C_s due to the gamma background is stronger for the double-gap RPC.

Cluster sizes

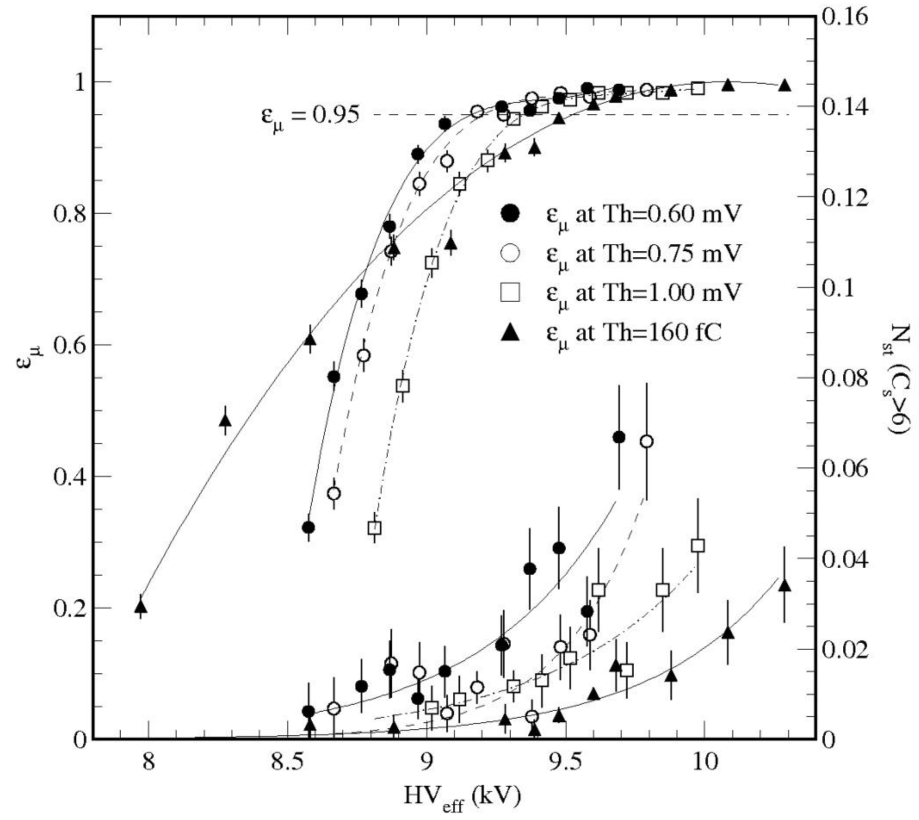




Four-gap RPC

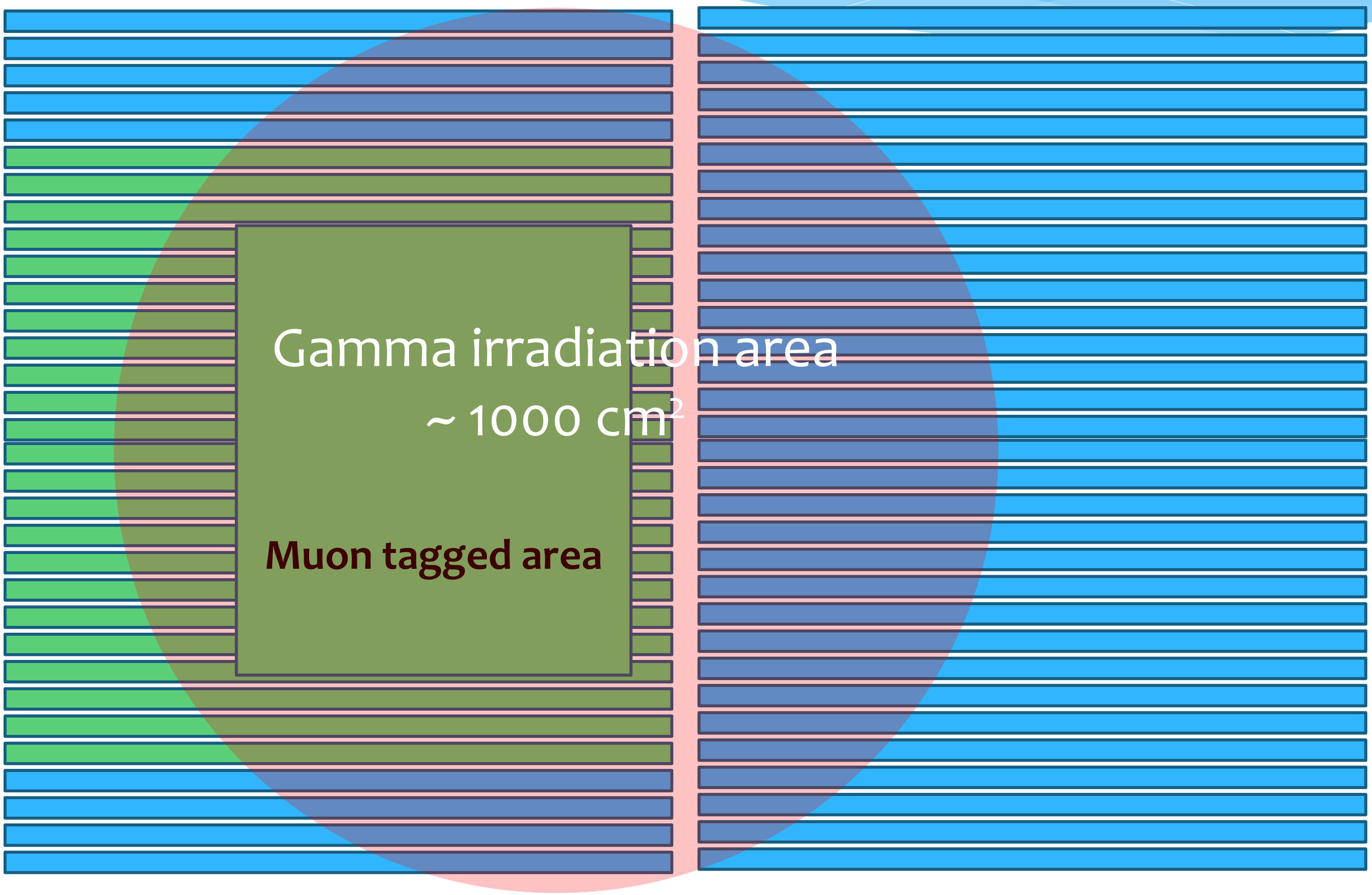


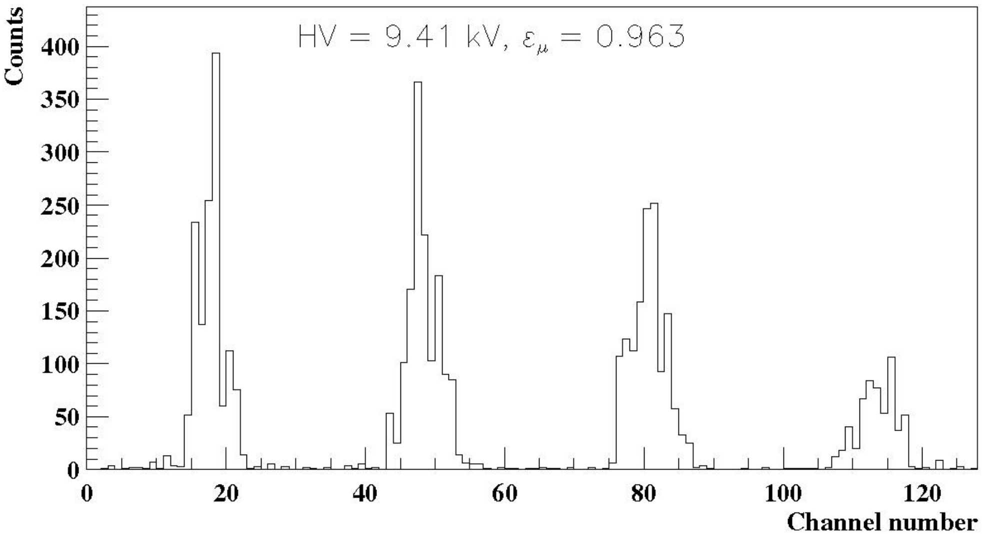
$\varepsilon_\mu = 0.95$
ε_μ at Th=0.60 mV
ε_μ at Th=0.75 mV
ε_μ at Th=1.00 mV
ε_μ at Th=160 fC
ε_μ
$C_{\sigma,\mu}$
HV_{eff} (kV)

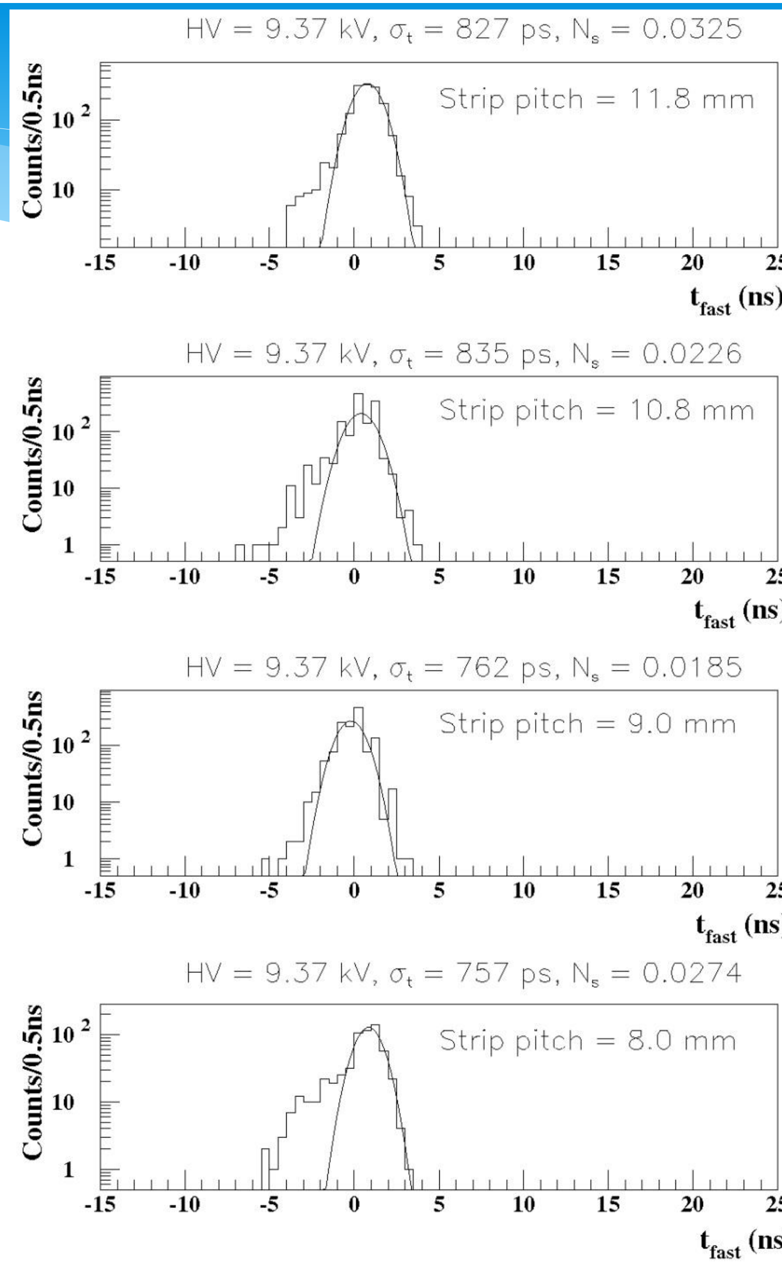


$\varepsilon_\mu = 0.95$
ε_μ at Th=0.60 mV
ε_μ at Th=0.75 mV
ε_μ at Th=1.00 mV
ε_μ at Th=160 fC
ε_μ
N_{st} (C_s>6)
HV_{eff} (kV)

Tagged muon hits in 16 μs windows
(from - 6 μs to + 10 μs centered at the muon peak)
(strip area affected by gamma hits ~ 500 cm²)




HV = 9.41 kV, ε_μ = 0.963
Counts
Channel number


HV = 9.37 kV, σ_t = 827 ps, N_s = 0.0325
Strip pitch = 11.8 mm
HV = 9.37 kV, σ_t = 835 ps, N_s = 0.0226
Strip pitch = 10.8 mm
HV = 9.37 kV, σ_t = 762 ps, N_s = 0.0185
Strip pitch = 9.0 mm
HV = 9.37 kV, σ_t = 757 ps, N_s = 0.0274
Strip pitch = 8.0 mm
Counts/0.5ns
t_{fast} (ns)

Bulk resistivity of the HPL

Can be measured by applying gamma-ray signals with rates close to the detection capability limit **(up to ~ 5 kHz cm^{-2})**

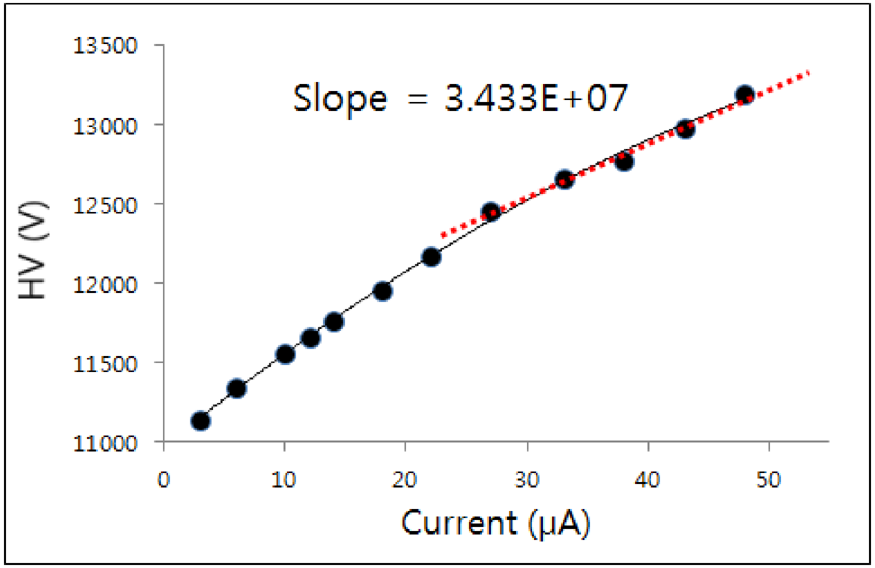
→ HV formed inside the gaps ~ insensitive to the increase of the applied HV

→ $\rho = (2.67 \pm 0.20) \times 10^{10}\ \Omega$ cm

Temperature coefficient **$\alpha = 0.13\ ^{o}C^{-1}$**

Irradiation area A ~ 500 cm^2, $d = 6 \times 0.2$ cm

$$\rho_b{}^{20} = \rho_T e^{\alpha(T - T_0)}$$



T = 24.97 C	P = 997.7 hPa	H = 73%

$$\Delta V = \rho * d/A\ \ \Delta I$$

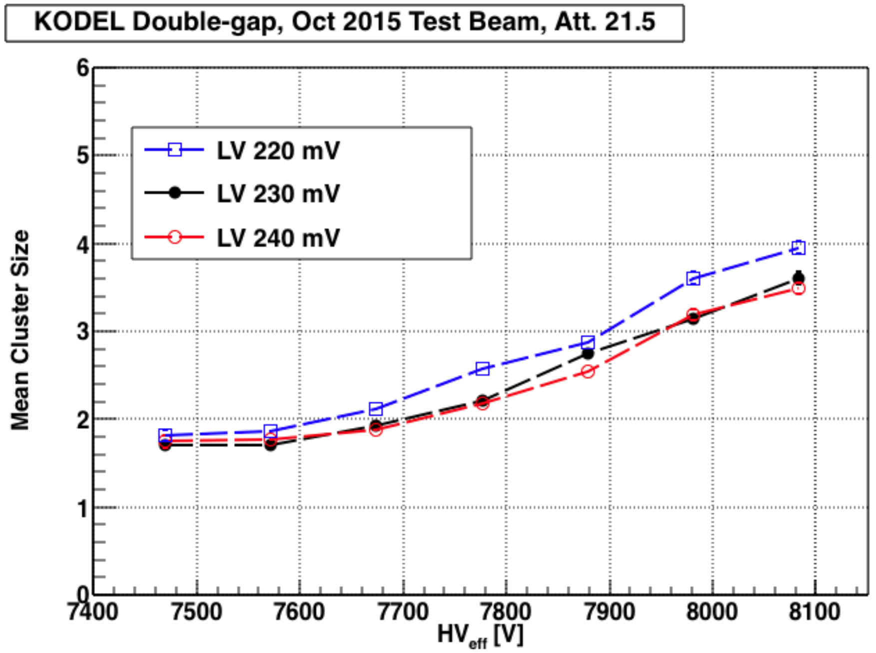
R	A/d	ρ(24.79)	ρ(20)
Ω	cm	Ω cm	Ω cm
3.433 E+07	416.67	1.4304 E+10	2.666 E+10

Threshold dependence of cluster sizes (muon beam only)

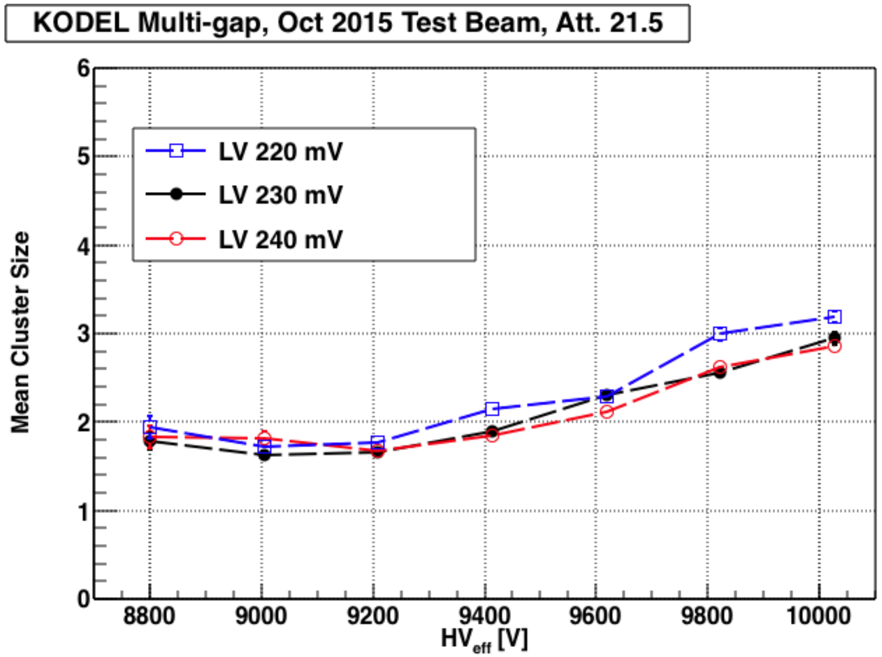
Both double-gap and multi-gap RPCs: **shift < 100 V.**

LV 220 mv ⇔ 170 fC
LV 230 mv ⇔ 190 fC
LV 240 mv ⇔ 240 fC

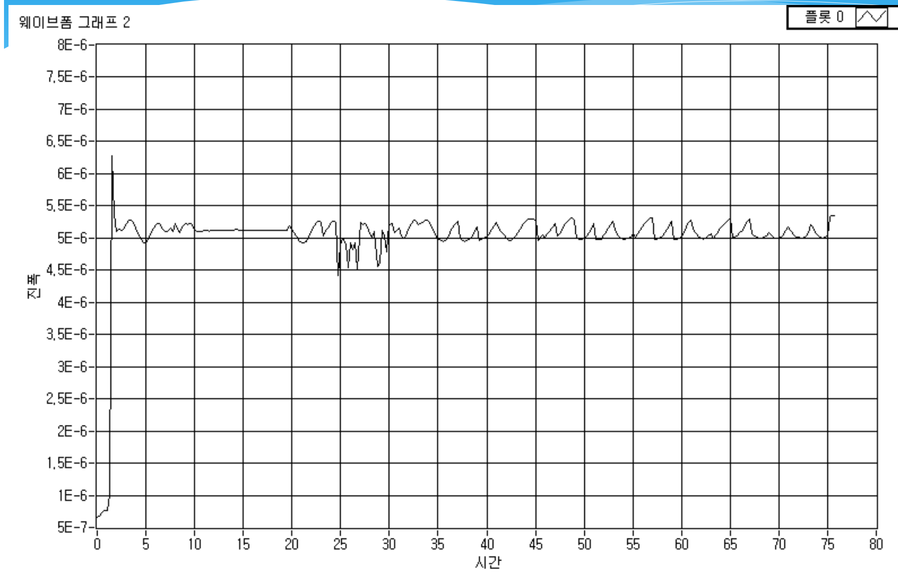
Double-gap RPC

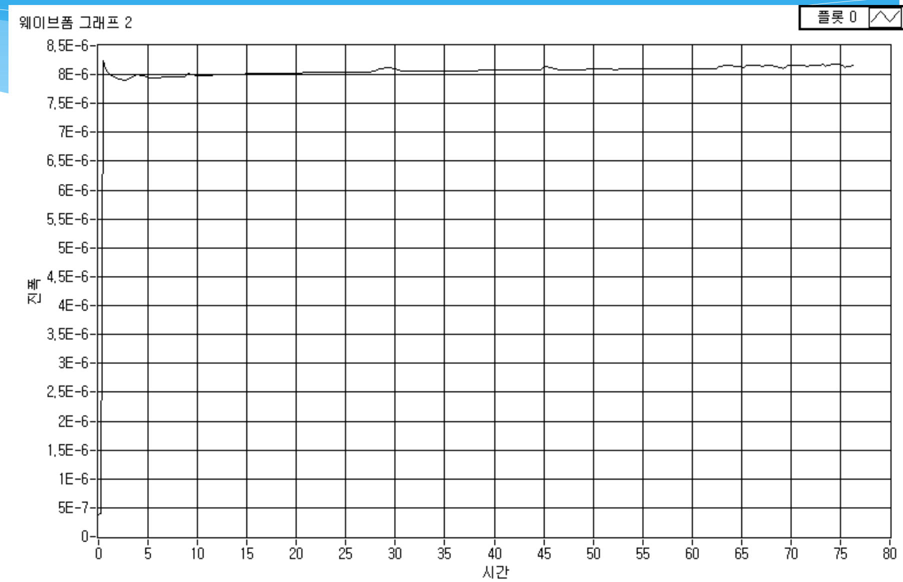


Multi-gap RPC



	HPL-resistivity value										24.6/ 45%/ 1009.3
	Current				Current				Current		
N.O	average	value	DATA LINK	N.O	average	value	DATA LINK	N.O	average	value	DATA LINK
1	7.84E-06	2.56E+10	01_graph	11	8.10E-06	2.48E+10	11_graph	21	7.50E-06	2.68E+10	21_graph
2	5.09E-06	3.95E+10	02_graph	12	8.29E-06	2.43E+10	12_graph	22	8.22E-06	2.45E+10	22_graph
3	8.07E-06	2.49E+10	03_graph	13	7.96E-06	2.53E+10	13_graph	23	8.41E-06	2.39E+10	23_graph
4	8.47E-06	2.37E+10	04_graph	14	8.14E-06	2.47E+10	14_graph	24	8.33E-06	2.41E+10	24_graph
5	8.43E-06	2.38E+10	05_graph	15	7.93E-06	2.53E+10	15_graph	25	8.03E-06	2.50E+10	25_graph
6	8.00E-06	2.51E+10	06_graph	16	8.32E-06	2.42E+10	16_graph	26	8.56E-06	2.35E+10	26_graph
7	7.59E-06	2.65E+10	07_graph	17	8.05E-06	2.50E+10	17_graph	27	8.30E-06	2.42E+10	27_graph
8	8.09E-06	2.48E+10	08_graph	18	8.22E-06	2.45E+10	18_graph	28	8.38E-06	2.40E+10	28_graph
9	8.40E-06	2.39E+10	09_graph	19	8.07E-06	2.49E+10	19_graph	29	7.48E-06	2.69E+10	29_graph
10	8.04E-06	2.50E+10	10_graph	20	7.90E-06	2.55E+10	20_graph				


웨이브폼 그래프 2
플롯 0
8E-6
7,5E-6
7E-6
6,5E-6
6E-6
5,5E-6
5E-6
4,5E-6
4E-6
3,5E-6
3E-6
2,5E-6
2E-6
1,5E-6
1E-6
5E-7
진폭
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
시간


웨이브폼 그래프 2
플롯 0
8,5E-6
8E-6
7,5E-6
7E-6
6,5E-6
6E-6
5,5E-6
5E-6
4,5E-6
4E-6
3,5E-6
3E-6
2,5E-6
2E-6
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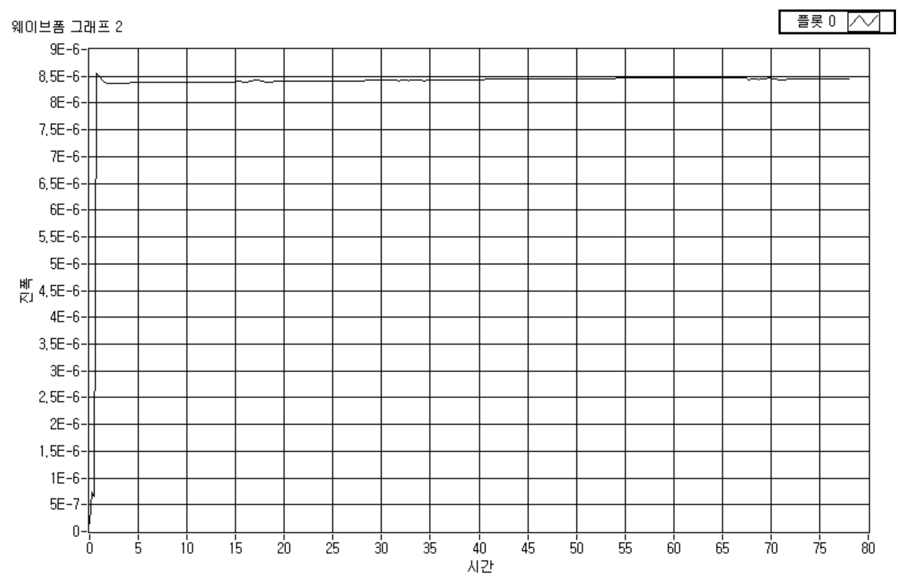
0
진폭
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
시간


웨이브폼 그래프 2
플롯 0
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7E-6
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6E-6
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5E-6
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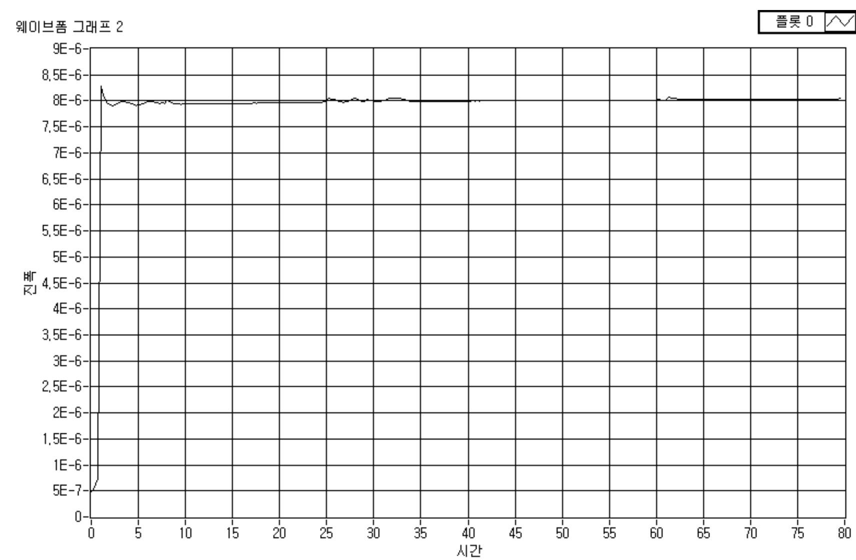
시간


웨이브폼 그래프 2
플롯 0
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8,5E-6
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7E-6
6,5E-6
6E-6
5,5E-6
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2E-6
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1E-6
5E-7
0
진폭
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
시간