Gas effect of MRPC in high luminosity experiment

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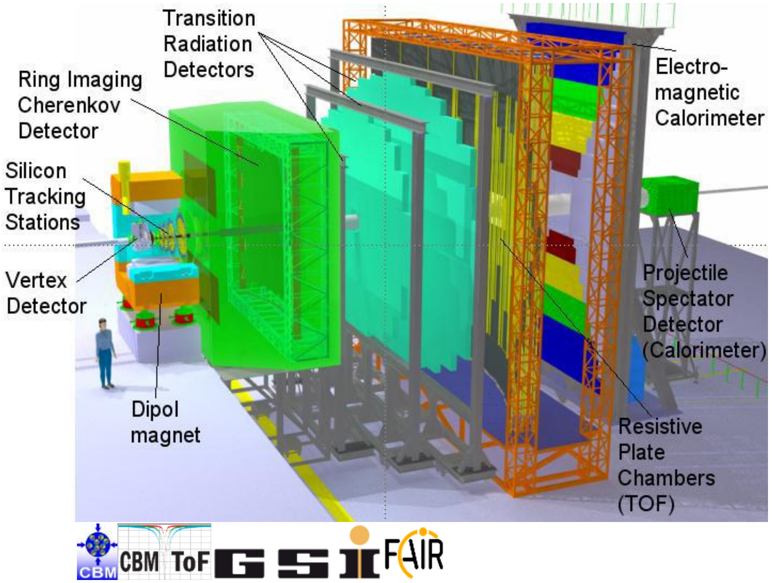
Outline

- Background Introduction
- Gas Pollution
- Simulation Based on SIMPLE Algorithm
- X-ray Experiments
- Design and Production of Self-Sealed MRPC
- The Next Working Steps
- Summary

Background: MRPC and CBM TOF

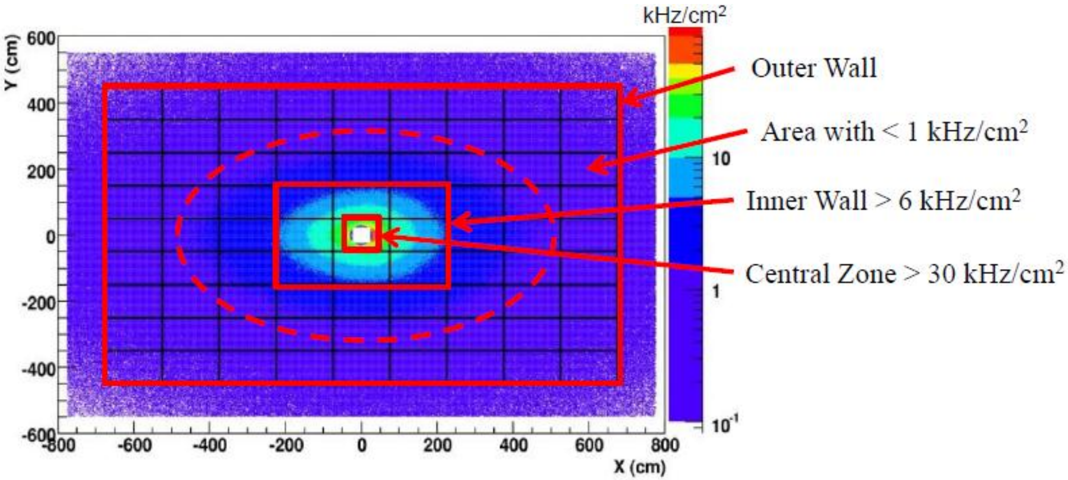


Multi-gap resistive plate chamber (MRPC) will construct the **time-of-flight system**(TOF) in the Compressed Baryonic Matter experiment(CBM) in FAIR, identifying secondary colliding particles.

CBM-TOF will work at very high rate, MRPC might meet problems for **long time** running under such **high luminosity** condition.

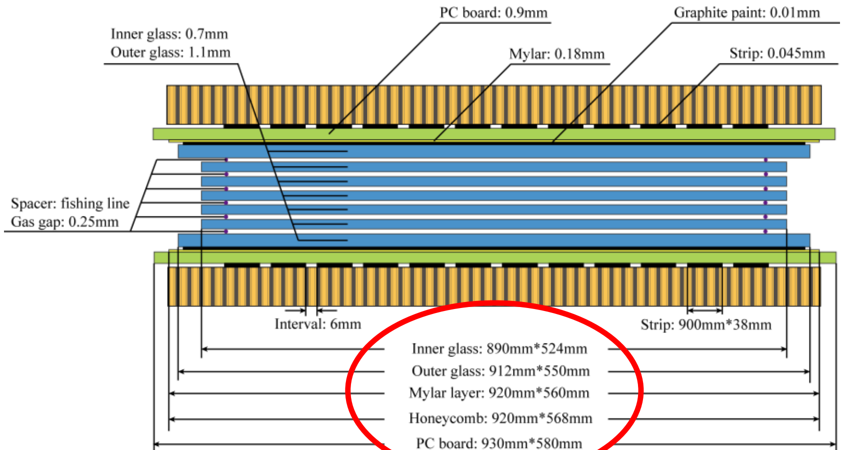
A simulation of charged particle flux for Au + Au events at 25AGeV assuming an interaction rate of 10MHz.

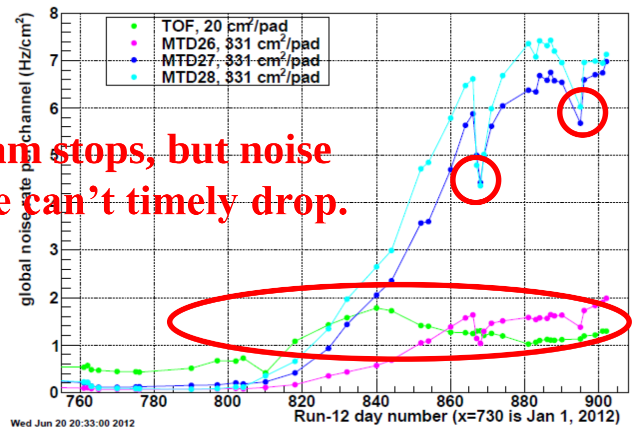
For high luminosity environment, the working gas is **consumed more rapidly**. The **interchange of gas** cannot be ignored any more.



Gas Pollution

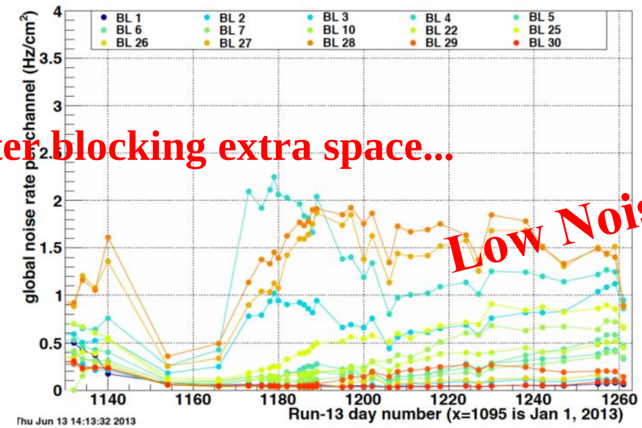
Working gas ($C_2H_2F_4$, iso-C_4H_{10}, SF_6) is exhausted more rapidly under high flux rate, and loses ability of **absorbing electron** and **suppressing streamer**. This effect was once observed on RHIC-STAR MTD.





Beam stops, but noise rate can't timely drop.

Large Size!



After blocking extra space...

Low Noise!

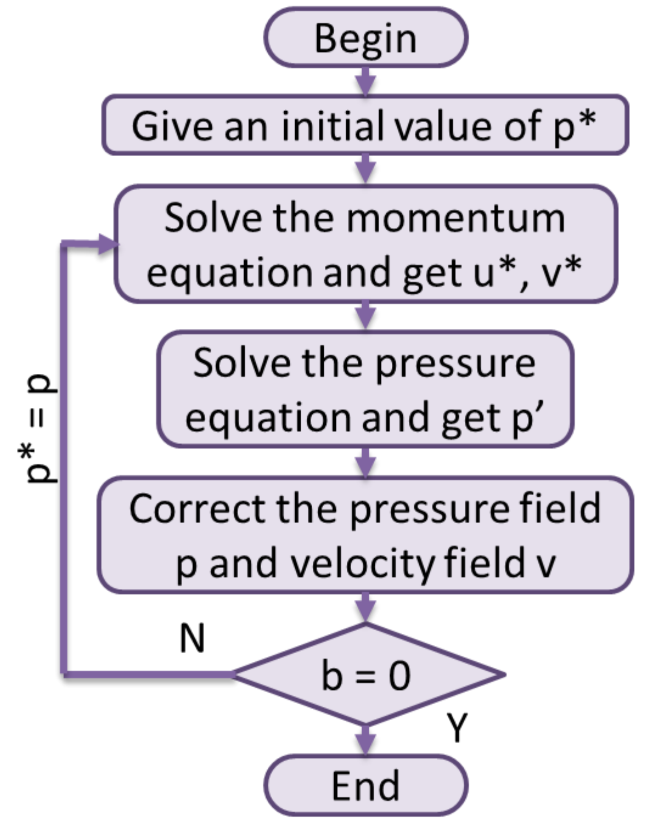
Simulation Based on SIMPLE Algorithm

A series of simulations are first conducted on the gas flow condition (flow velocity, gas concentration, etc.) in the MRPC counter, including a **two-dimensional simulation** based on **SIMPLE algorithm**.

Governing Equation:

$$\underbrace{\frac{\partial(\rho\phi)}{\partial t}}_{\text{Unsteady}} + \underbrace{\nabla\cdot(\rho\vec{v}\phi)}_{\text{Advection}} = \underbrace{\nabla\cdot\left(\Gamma_\phi\nabla\phi\right)}_{\text{Diffusion}} + \underbrace{S_\phi}_{\text{Source}}$$

Finite volume method (FVM) ;
SIMPLE algorithm (Semi-Implicit Method for Pressure-Linked Equations)

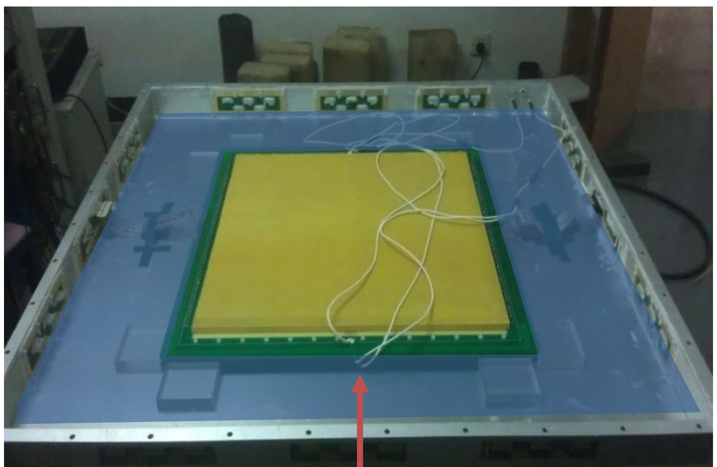


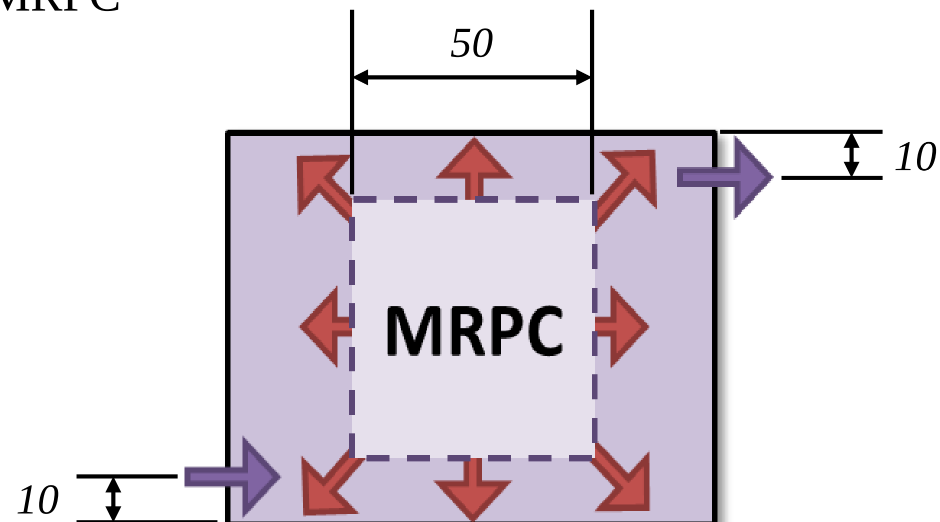
Simulation: Establishing Model

To simplify the situation, a **two-dimension model** is established.

Parameter in consideration: **gas volume**, **flow rate**, **pollution concentration**

Parameter ignored: 3-D structure of MRPC





Calculating field: the horizontal transect of the gas box with MRPC inside at the level of a gas gap.

Grid size: 1cm x 1cm;
MRPC area: 50 x 50 grid
Inlet & Outlet: 10 grid

Simulation: Governing Equation

According to the situation, the **governing equation** includes 3 parts.

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

Density of gas ρ is constant, so it won't appear in this equation.

Momentum equation:

$$\rho\frac{\partial u}{\partial t}+\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

$$\rho\frac{\partial v}{\partial t}+\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)$$

Assume gas viscosity is constant and the gas cannot be compressed.

Component equation:

$$\rho\frac{\partial c}{\partial t}+\rho\left(u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}\right)=\Gamma_l\left(\frac{\partial^2 c}{\partial x^2}+\frac{\partial^2 c}{\partial y^2}\right)+R_l$$

Two kinds of gas, this component equation is essential.

c - massive percentage of polluted; Γ_l - diffusion coefficient of polluted gas; R_l - generating rate per unit volume

Simulation: Parameter Determination

Some parameters has to be determined to solve governing equations.

Gas density ρ: Take $C_2H_2F_4$'s density: $\rho = 1.21\mathrm{kg/m^3}$

Gas dynamic viscosity μ: Take $C_2H_2F_4$'s viscosity: $\mu = 0.022\mathrm{mPa\cdot s}$

Gas inlet velocity UIN: With gas flow rate 60mL/min and inlet diameter 1cm:

$$\mathrm{UIN} = \frac{60}{60\times\pi\times 0.5^2}\times\frac{1}{100} = 0.0127\,\mathrm{m/s}$$

Polluted gas generating rate R_l:

Flux rate of incident particles: 25 $\mathrm{kHz/cm^2}$
Assume average deposited energy of incident particles is 10MeV
Average ionization energy of gas is 30eV
Avalanche amplification factor is 10^6

Gas molecules polluting rate

$$R_p = 25\times 10^7\times\frac{10^7}{30}\times 10^6 \approx 8.333\times 10^{19}$$

$$R_t = \frac{1210\times 1\times 1\times 0.001}{102}\times 6.02\times 10^{23}\approx 7.141\times 10^{21}$$

Total number of gas molecules per square meter

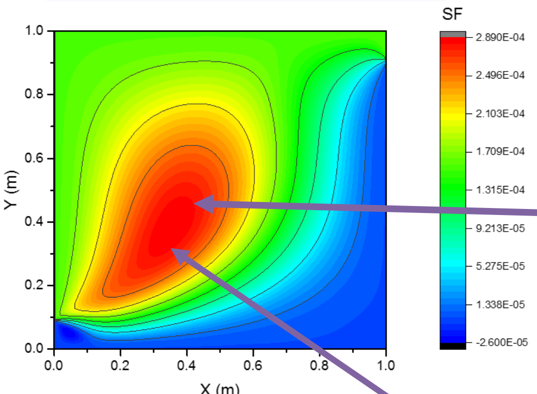
$$R_l = \frac{R_p}{R_t}\cdot\rho = \frac{8.333\times 10^{19}}{7.141\times 10^{21}}\times 1.21\approx 0.01412\mathrm{kg/(s\cdot m^3)}$$

Simulation: Standard Situation

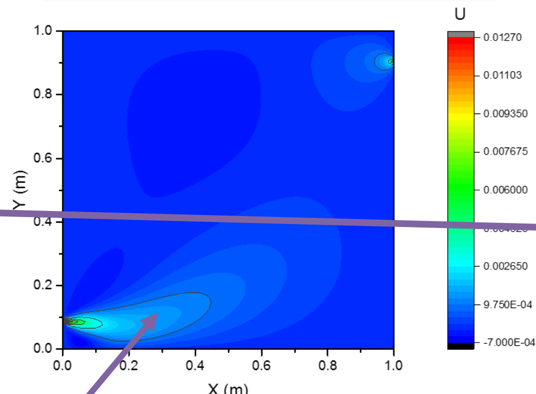
Take a possible experimental condition as **standard situation**:

Gas box volume: 1m x 1m; Gas flow: 60mL/min

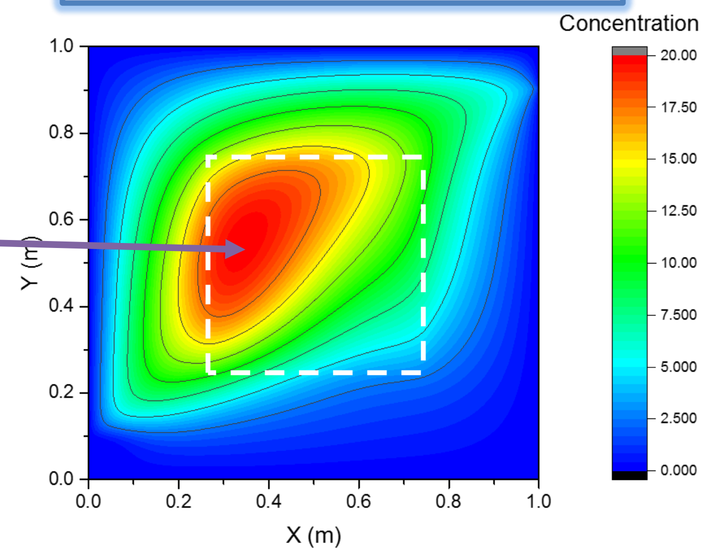
Flow Distribution



Velocity Distribution



Concentration Distribution



A vortex caused by jet entrainment

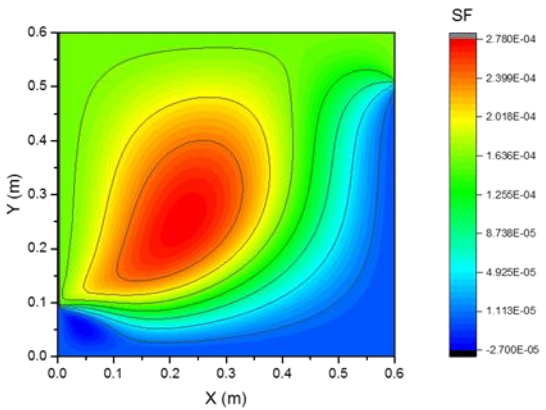
Flow distribution has a critical impact on pollutants concentration in gas box! Most polluted area is **not in the center of gas box**.

White square: MRPC area.
Max concentration: **20%**.

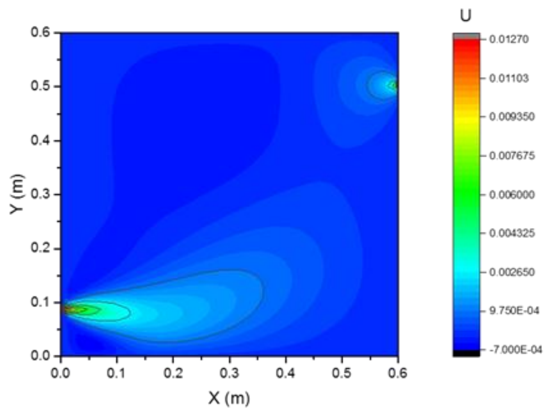
Simulation: Flow Volume

Decrease the gas box volume (like blocking extra space in STAR) in simulation:
Box Volume: 60cm x 60cm. Gas Flow: 60ml/min.

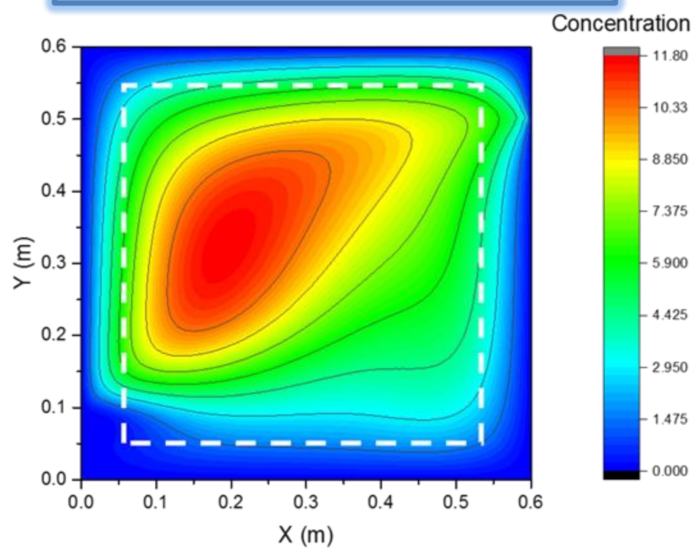
Flow Distribution



Velocity Distribution



Concentration Distribution

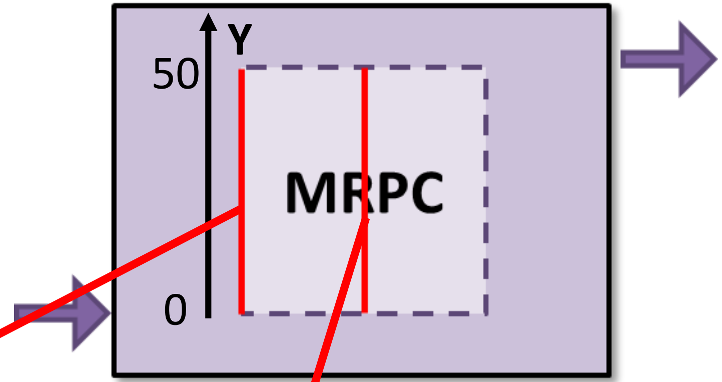


Flow distribution nearly keeps the same with standard condition.

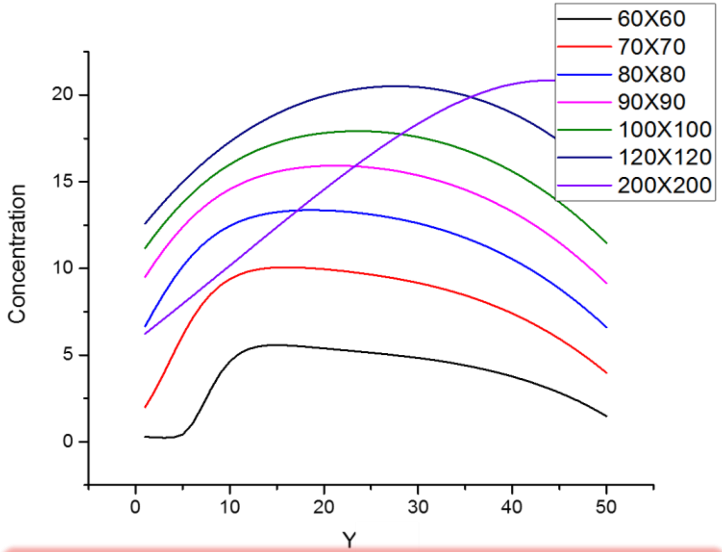
Max concentration: **11.8%**; Concentration reduces to half compared to standard situation.

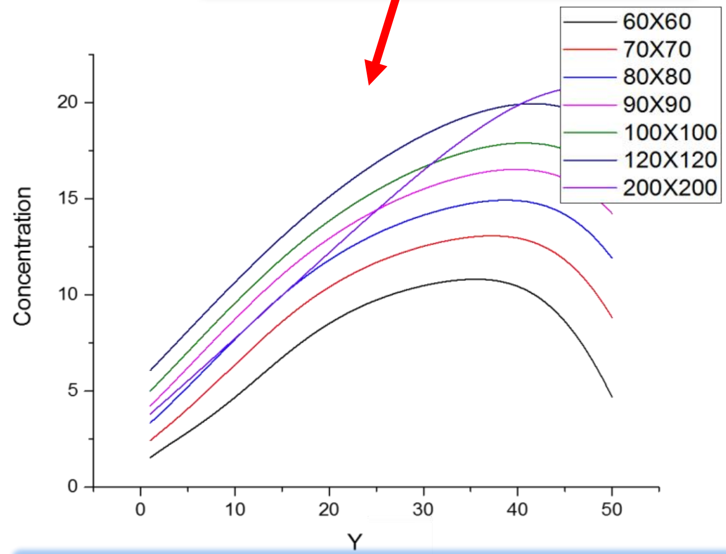
Simulation: Flow Volume

Test different volume in simulation:
Box Volume: 60cm; 70cm; 80cm; 90cm, 100cm; 120cm; 200cm. Gas Flow: 60ml/min.



Concentration at left boundary of MRPC of different gas box volume



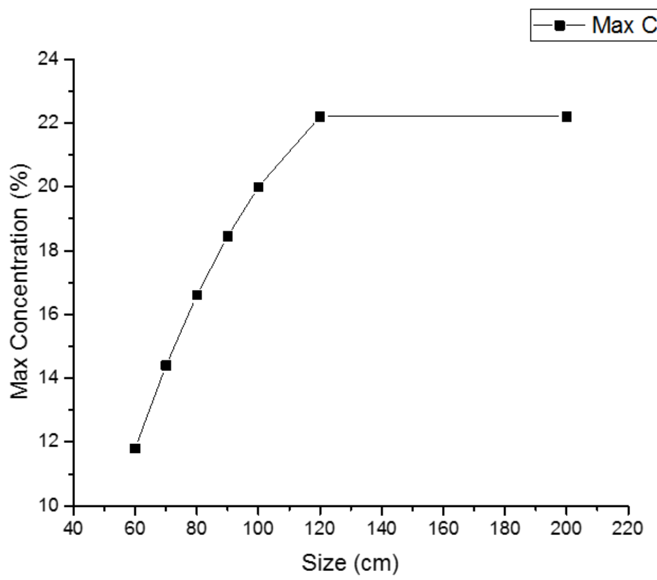


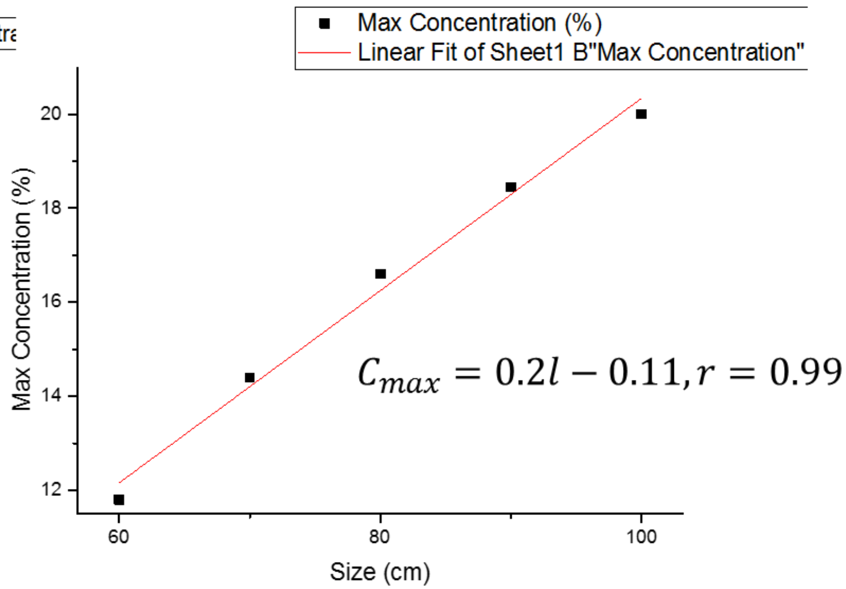
At 2.0 meter, the curve is shifted along Y axis.

Concentration at center of MRPC of different gas box volume

Simulation: Flow Volume

Test different volume in simulation:
Box Volume: 60cm; 70cm; 80cm; 90cm, 100cm; 120cm; 200cm.
Gas Flow: 60ml/min.





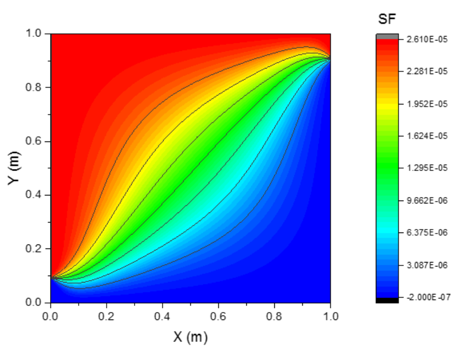
Max concentration keeps growing with volume increasing until it's large enough (120cm x 120cm).

Below 100cm x 100cm volume, the relationship between max concentration and volume is **linear**.

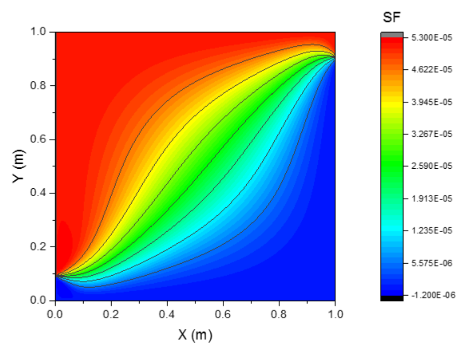
Simulation: Gas Flow

Modify different gas flow speed in simulation:
Gas Flow: 10ml/min; 20ml/min; 40ml/min; 60ml/min. Box Volume: 1m x 1m.

Flow Distribution

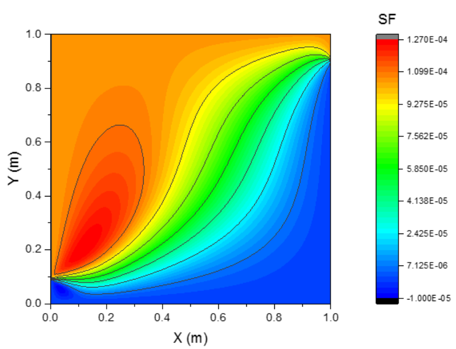


10ml/min

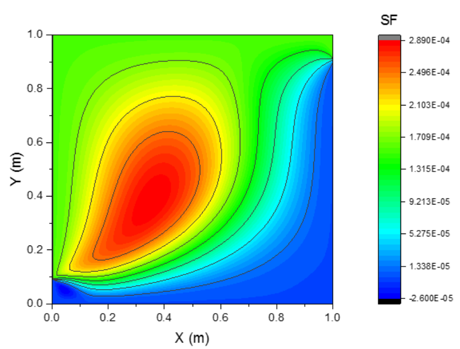


20ml/min

When the gas inlet velocity is relatively low, there is **no jet entrainment**. Gas flows directly from inlet to outlet.



40ml/min



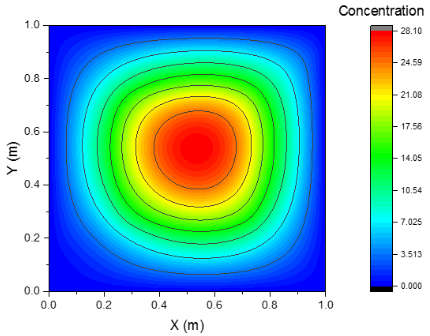
60ml/min

When increasing gas flow rate, **jet entrainment** becomes more and more obvious a factor.

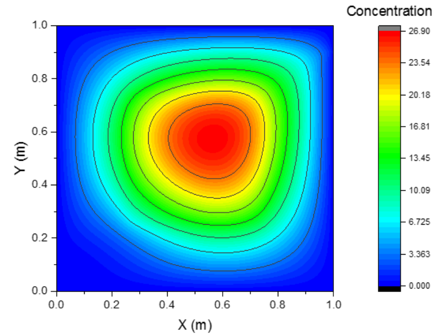
Simulation: Gas Flow

Modify different gas flow speed in simulation :
Gas Flow: 10ml/min; 20ml/min; 40ml/min; 60ml/min. Box Volume: 1m x 1m.

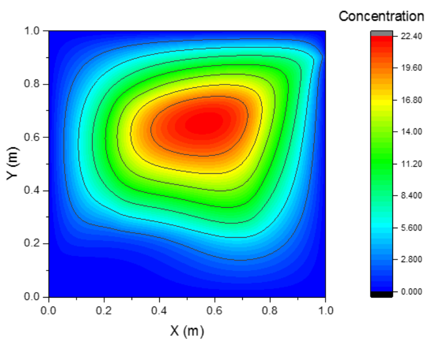
Concentration Distribution



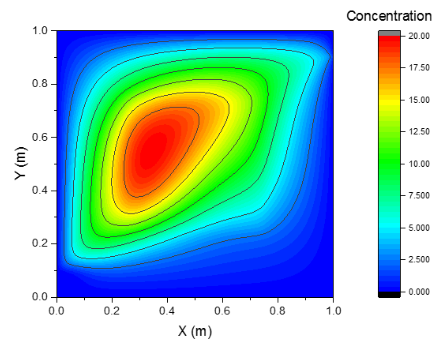
10ml/min



20ml/min

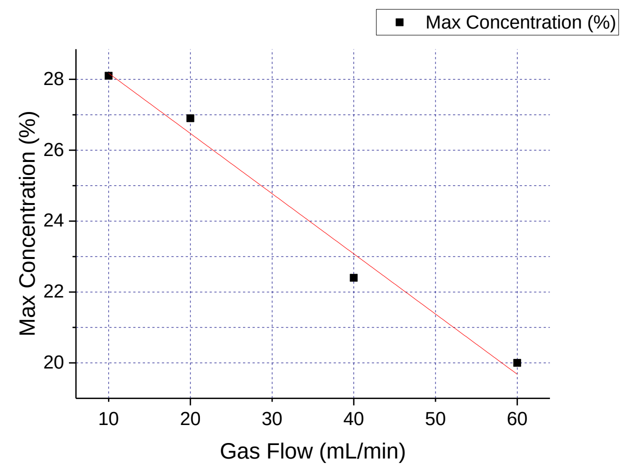


40ml/min



60ml/min

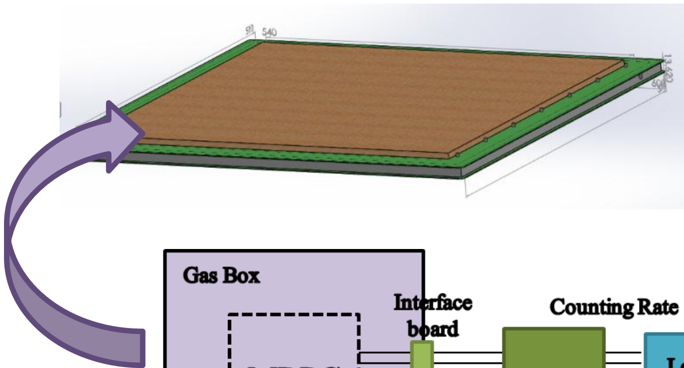
Max Concentration under Different Gas Flow

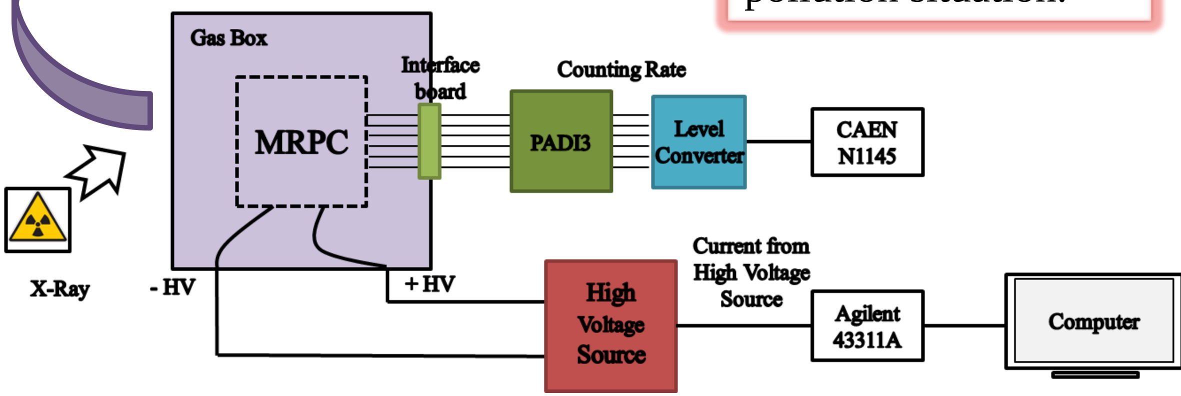


Max concentration **drops linearly** with gas velocity increasing.

X-ray Test: Experimental Setup

Design a **8-gap** MRPC with **double chamber**. Parameters are as follows:





Design large counter size for more obvious result under gas pollution situation.

MRPC Part	Design Size/mm
Bottom PCB	580×610
Middle PCB	542×554
Outer glass	505×529
Inner glass	495×519
Mylar	509×533
Honeycomb board	500×510
Gas gap width	0.25
Gas gap number	8
Strip width	7
Strip length	50
Strip gap	3
Strip number	48
Detection area	480×500
Gas box size	1000×1000×60

A high intensity **X-ray source** to simulate high particle flux condition, **dark current recovery time** involved for measuring gas pollution. Freon(90%) + iso-C_4H_{10}(5%) + SF_6 (5%).

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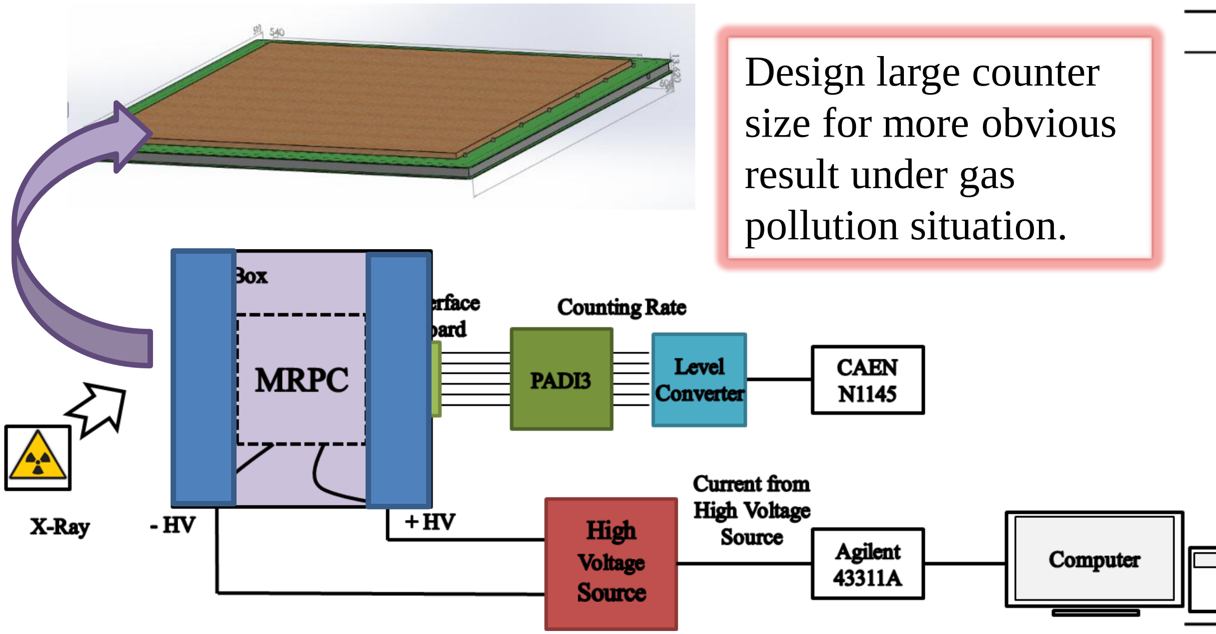

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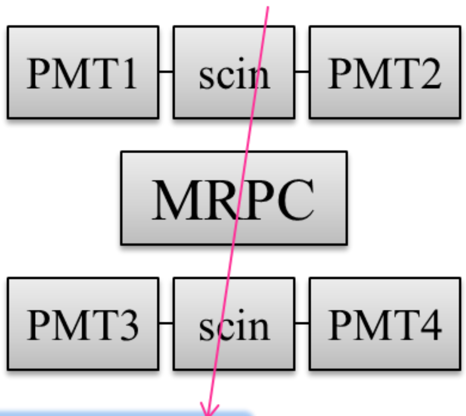
A high intensity **X-ray source** to simulate high particle flux condition, **dark current recovery time** involved for measuring gas pollution. Freon(90%) + iso-C4H10(5%) + SF6 (5%).

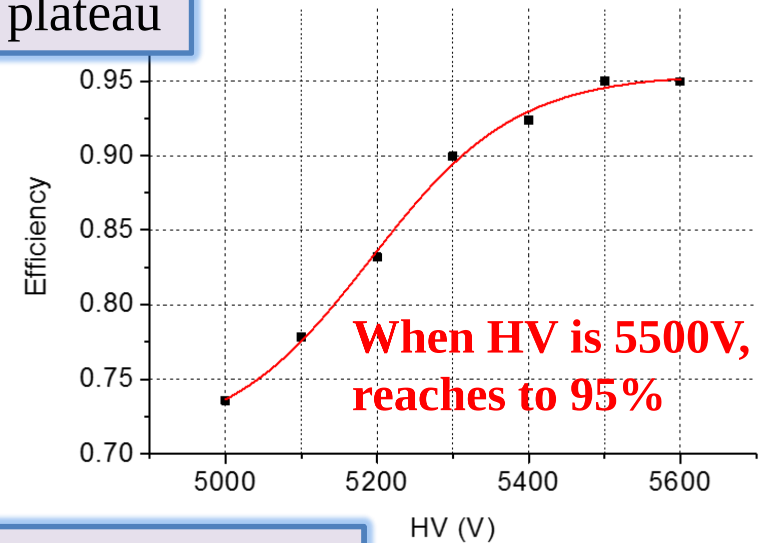
Block extra space in the gas box; Change other parameters of X-ray & gas.

Experimental Results: Cosmic-Ray Test & X-Ray Test

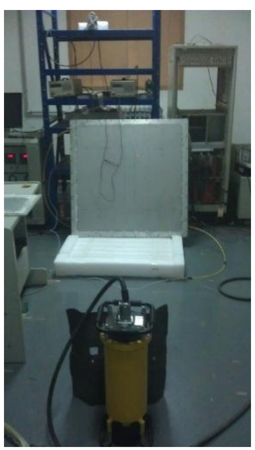
Cosmic-Ray Test

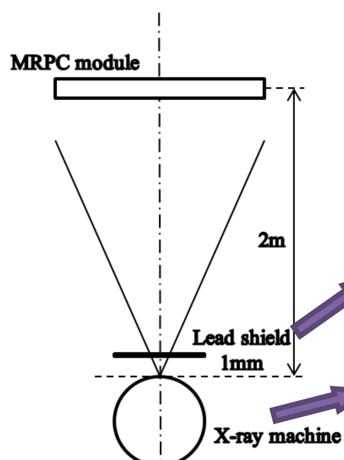


Efficiency plateau



X-Ray Test

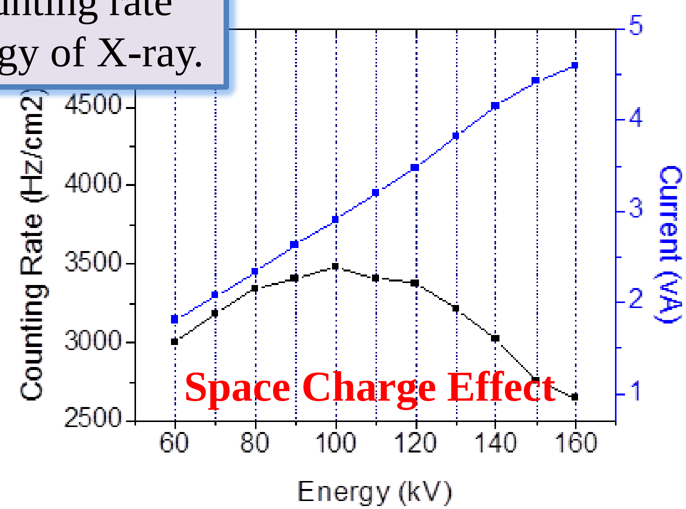




Prevent it from too intense.

Simulate high luminosity beam.

Dark current and counting rate as a function of energy of X-ray.



Experimental Results: X-Ray Test

Influence of X-ray's during time and energy to the MRPC counter.

MRPC HV: 5500V
Gas flow: 54-3-3(ml/min)
X-ray energy: 60kV
X-ray during time: 1min/2min/5min

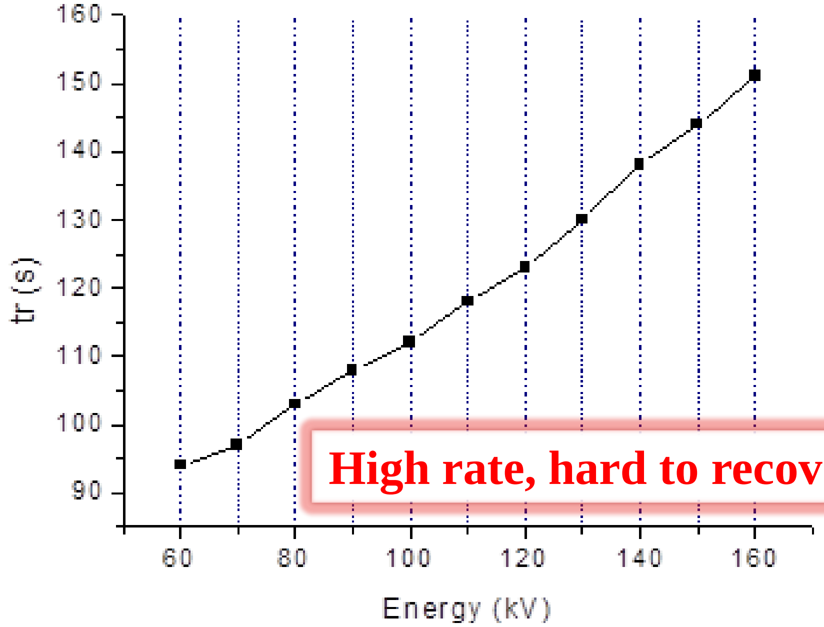
MRPC HV: 5500V
Gas flow: 54-3-3(ml/min)
X-ray energy: 60kV~160kV
X-ray during time: 2min

t_r - Recovery time

- estimate how fast counter can recover from gas pollution.

Irradiation Time	t_r / s
1min	91
2min	96
5min	89

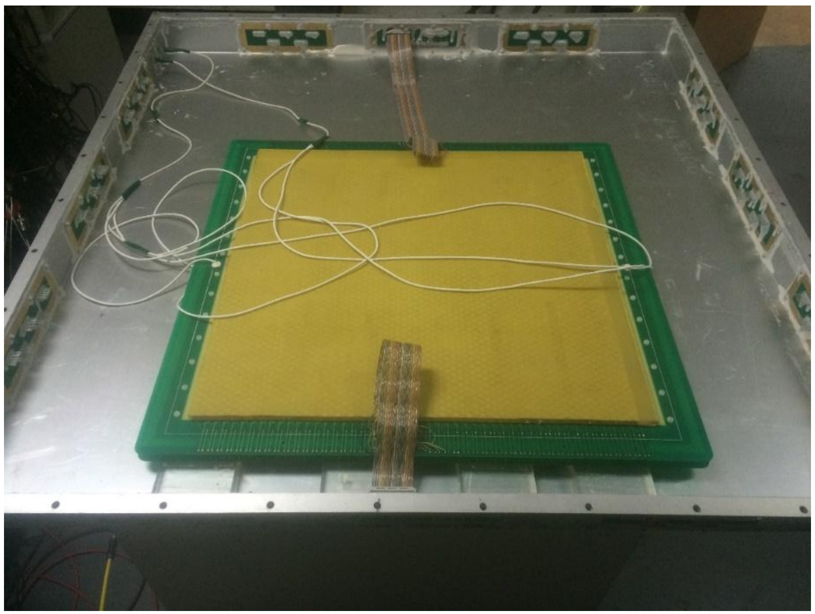
Short time: Not obvious

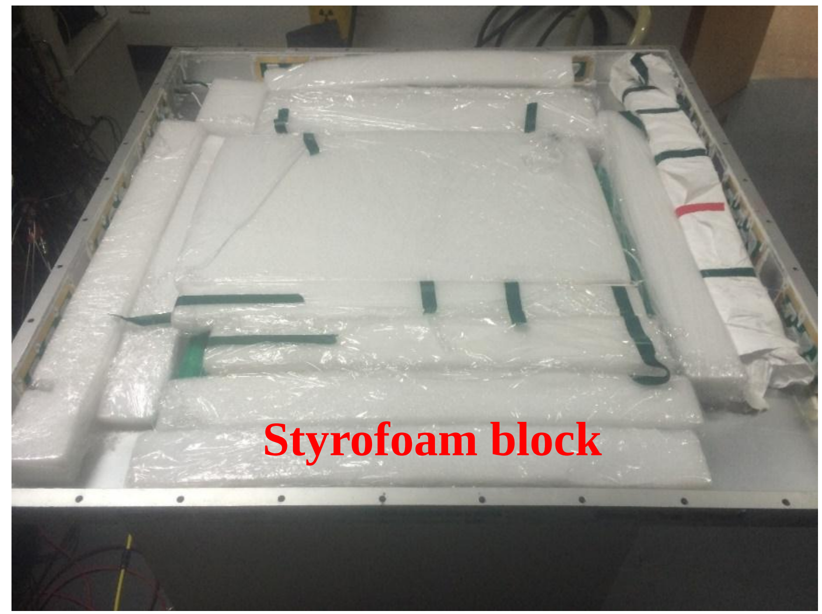


High rate, hard to recover

Experimental Results: Block Test

We **block** the extra space in the gas box (reducing the volume as in the simulation), and check if the gas **interchanges faster**.





Normal setting:

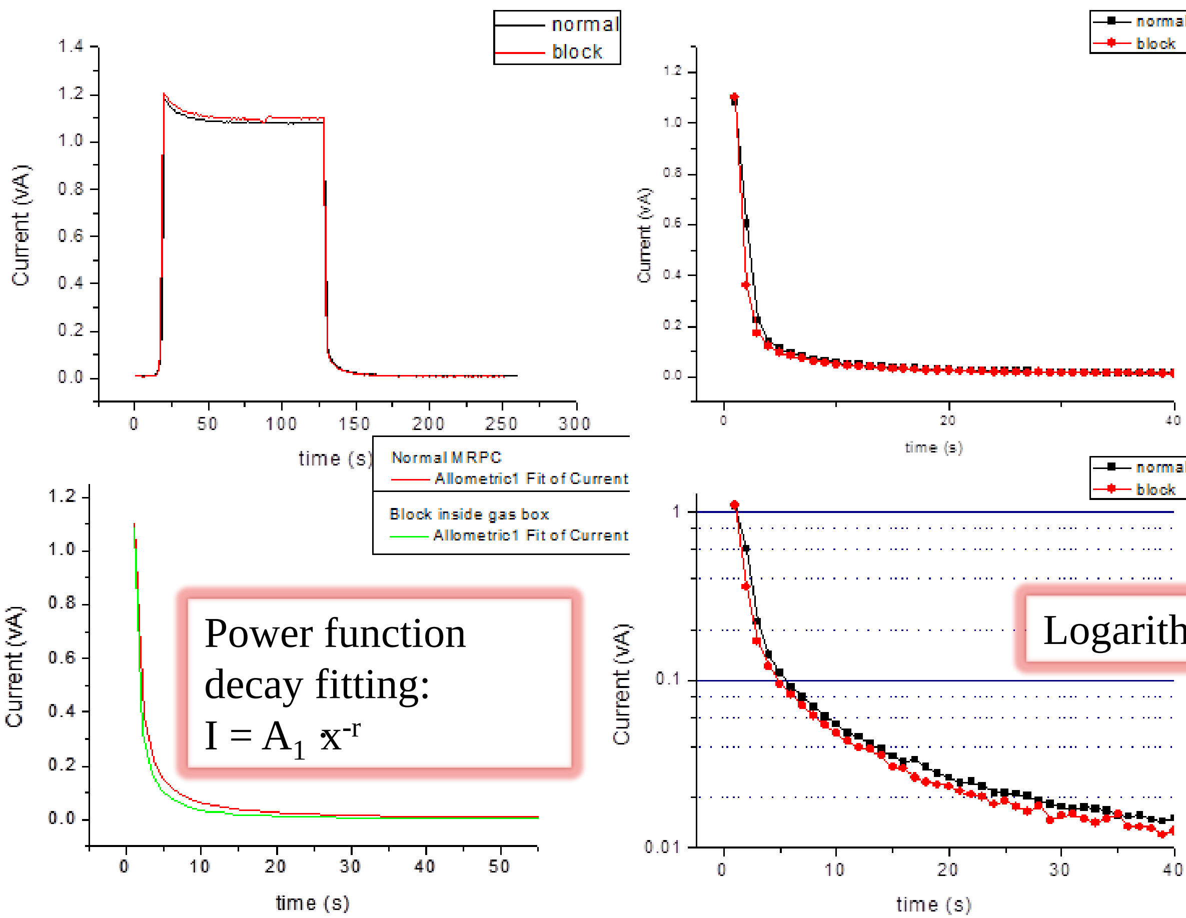
Volume of gas box:	64.5L
Volume of chamber:	25.6L
Volume of gas:	**39L**

Block setting:

Volume of block:	21.3L
Volume of gas:	**18L**

Experimental Results: Block Test

MRPC HV: 5500V; Gas flow: 54-3-3(ml/min); X-ray energy: 60kV; X-ray during time: 2min; Leadshield:1mm; Distance:3m.



Power function decay fitting:
$I = A_1 \, x^{-r}$

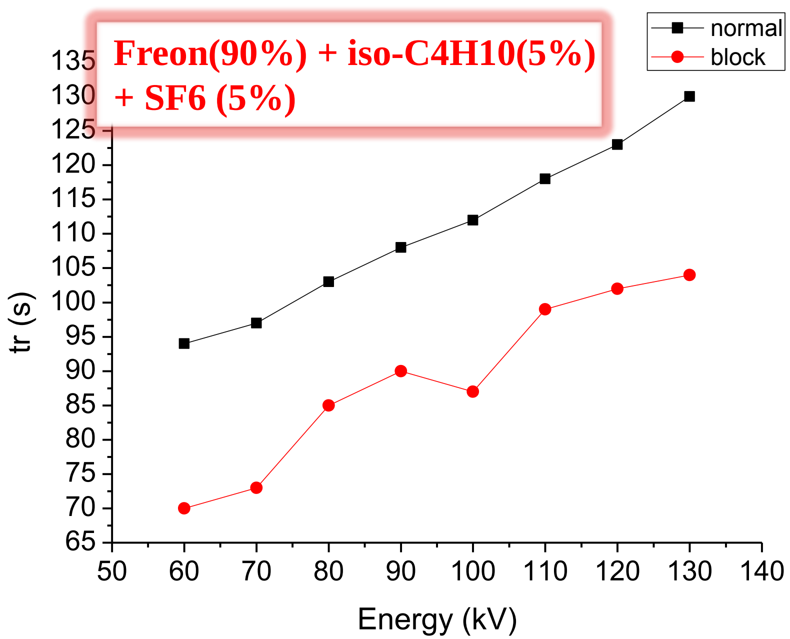
Logarithmic coordinate

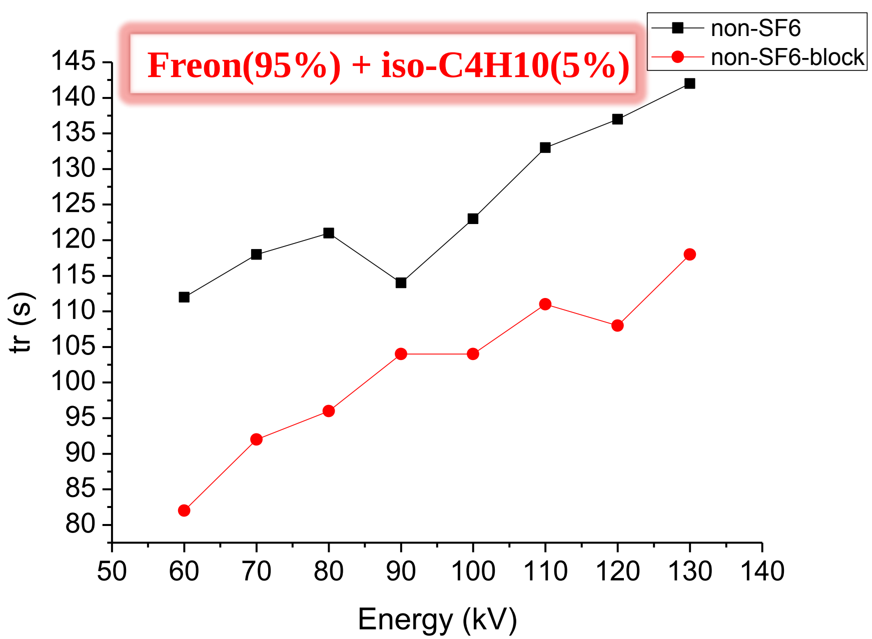
Experimental Results: Block Test

t_r as a function of **X-ray's energy** - block setting MRPC always recovers faster than normal one, both in the original gas mixture and non SF_6.

MRPC HV: 5500V; **Gas flow: 54-3-3 (ml/min);**
X-ray energy: 60kV; X-ray during time: 2min
Leadshield:1mm; Distance:3m.

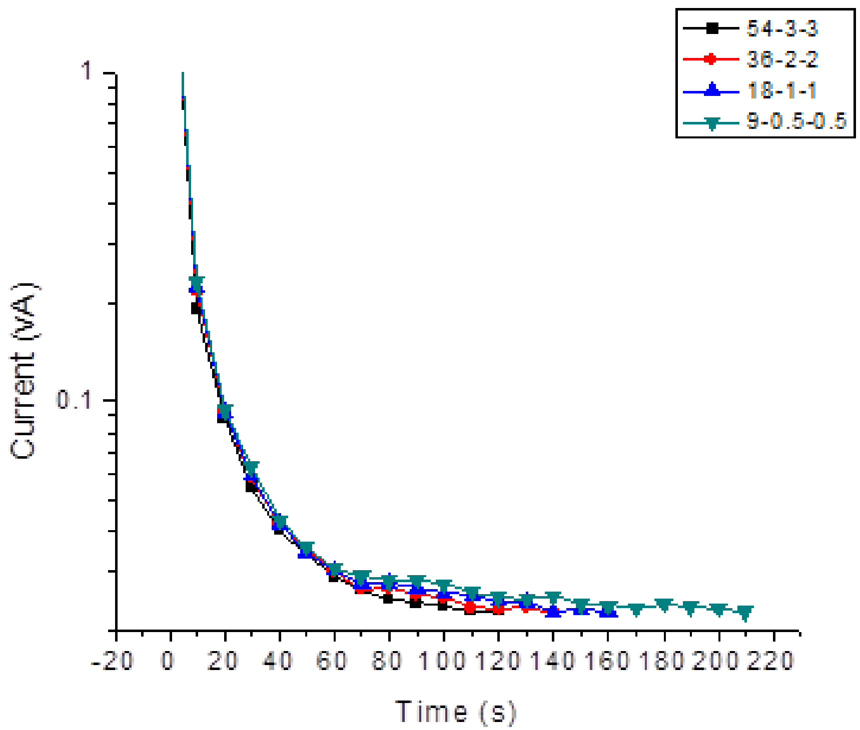
MRPC HV: 5500V; **Gas flow: 57-3 (ml/min);**
X-ray energy: 60kV; X-ray during time: 2min
Leadshield:1mm; Distance:3m.



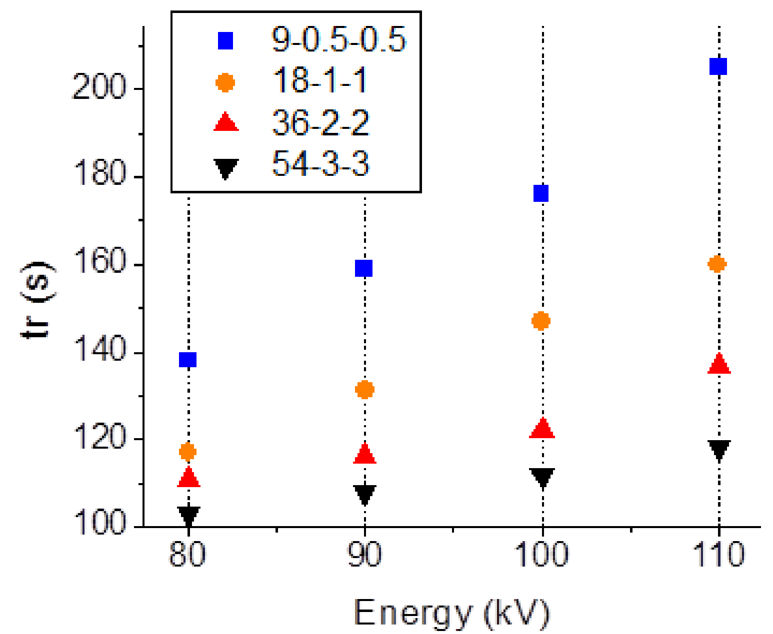


Experimental Results: Gas Flow Test

Gas flow: 54-3-3/36-2-2/18-1-1/9-0.5-0.5 (ml/min); X-ray energy: 110kV; X-ray during time: 2min; Leadshield:1mm; Distance:3m.



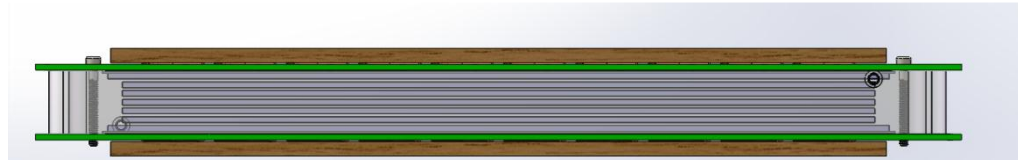
Different X-ray's energy, variation of recovery time along with gas flow remains the same.



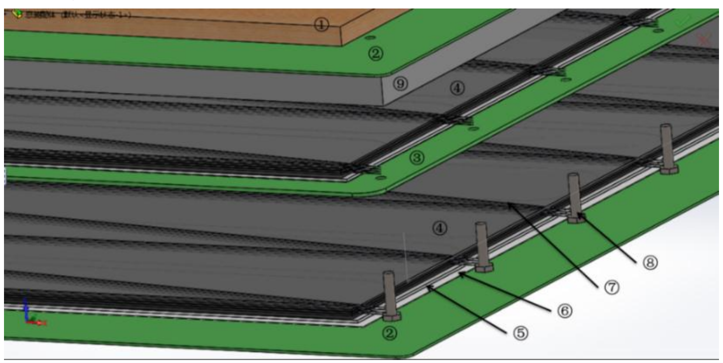
Gas flow decreases, current drops slower. Fitting simulation results quite well.

Self-Sealed MRPC: Introduction

- Gas pollution is related to the module size.
- Reduce the volume.
- Eliminate the Aluminum box and make MRPC self-seaed.

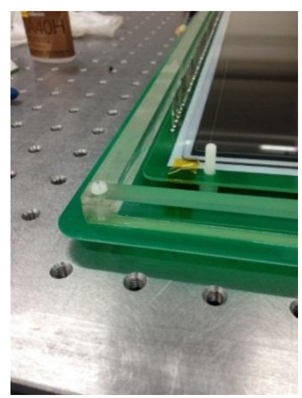


Self-sealed MRPC's side is **sealed by PMMA**, enables it **work independently**.



①Honeycomb board; ②Bottom PCB; ③Middle PCB; ④Inner glass; ⑤Outer glass; ⑥Mylar; ⑦Nylon fishing line; ⑧Nylon column; ⑨PMMA strip.

Prototype: Except the **PMMA strip**, other parameters are the **same**.



Before test, 3~5 times MRPC module's volume working gas needs charging to exhaust air.

Normal MRPC:
Volume for gas: 64.5L

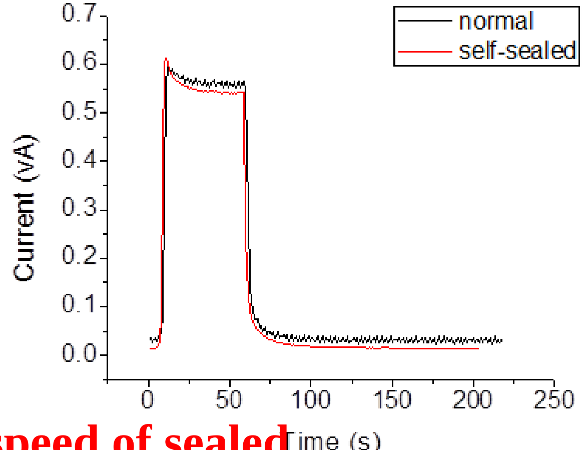
For 60ml/min gas flow, 53h.

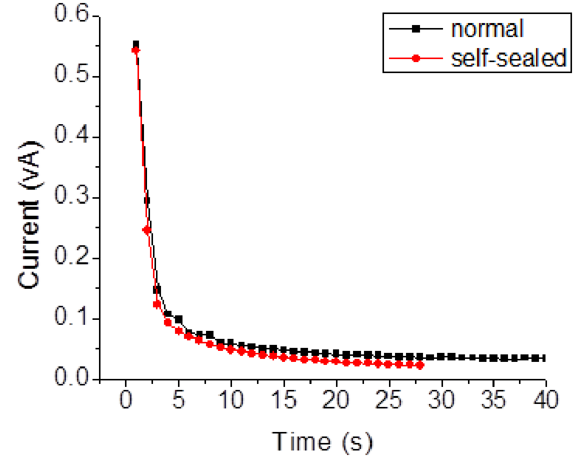
Self-sealed MRPC:
Volume for gas: 2.5L

For 60ml/min gas flow, 2h.

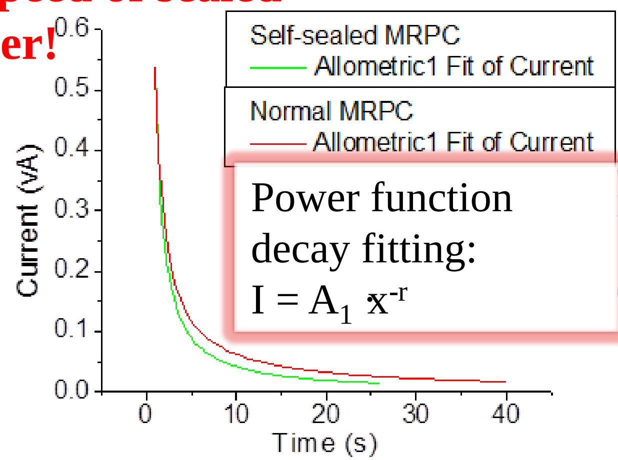
Self-Sealed MRPC: Experimental Results

MRPC HV: 5500V; Gas flow: 54-3-3(ml/min); X-ray energy: 60kV; X-ray during time: 1min; Leadshield:1mm; Distance:3m.



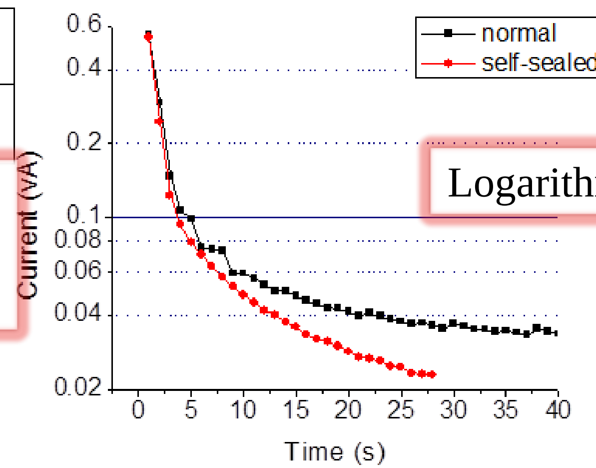


Restoration speed of sealed MRPC is faster!



Power function decay fitting:

$I = A_1 x^{-r}$

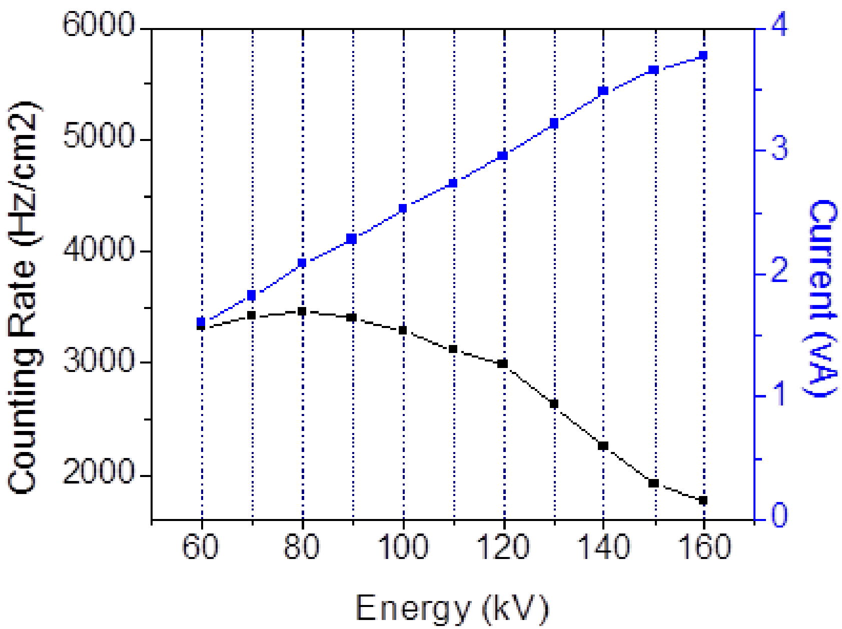


Logarithmic coordinate

Self-Sealed MRPC: Experimental Results

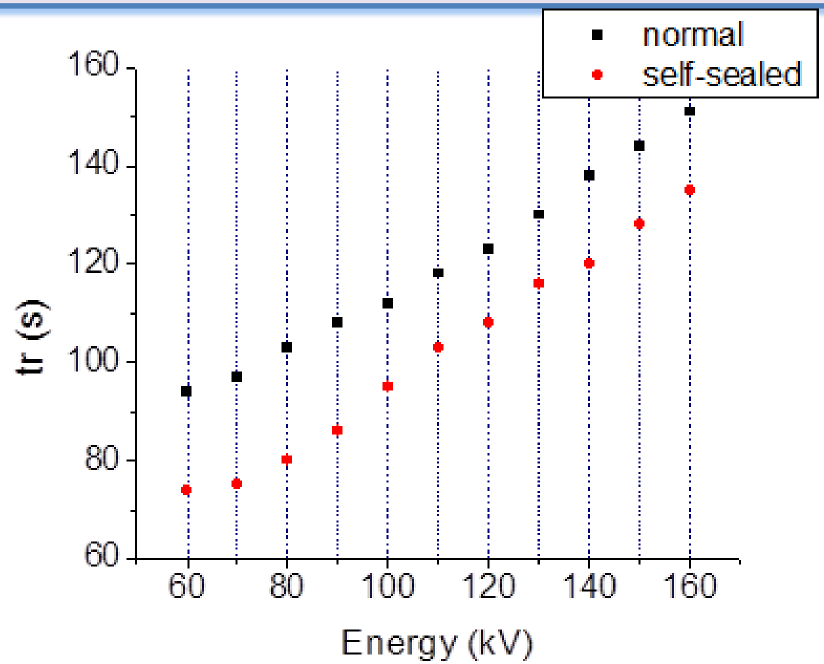
Dark current and **counting rate** as a function of **energy of X-ray** for self-sealed MRPC.

MRPC HV: 5500V; Gas flow: 54-3-3 (ml/min); X-ray energy: 60~160kV; X-ray during time: 2min; Leadshield:1mm; Distance:3m.



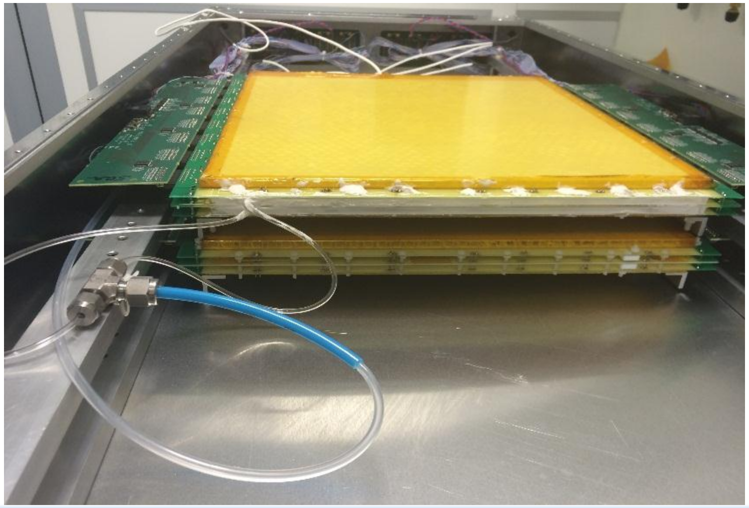
t_r as a function of **X-ray's energy** - sealed MRPC always recovers faster than normal one.

MRPC HV: 5500V; Gas flow: 57-3-3 (ml/min); X-ray energy: 60~160kV; X-ray during time: 2min; Leadshield:1mm; Distance:3m.



Next Working Steps

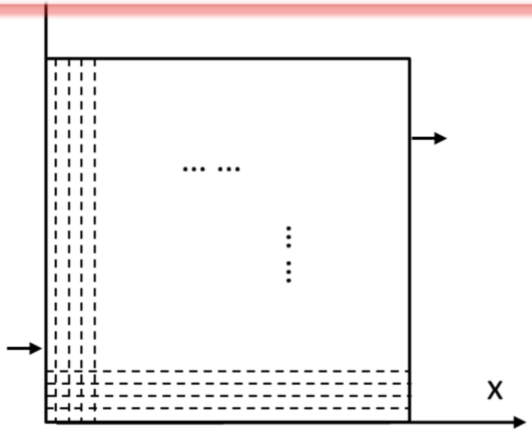
Further study on **gas pollution** and **self-sealed MRPC** from two aspects —— **experiment and simulation**, should be carried on.



Present simulation is a much too simplified estimation.

More realistic parameter determination;
More concerns about geometrical details;
More conditions to simulate;
A 3-D simulation;
… …

A MRPC prototype was operated in the CERN 2015 Nov beam time, the performance (dark current, efficiency, time resolution, etc.) is under analysis.



Newly-designed self-sealed MRPC will be manufactured.

Summary

- With increase of accelerator luminosity, gas is consumed more rapidly and becomes a problem for MRPC.
- Simulation based on SIMPLE algorithm shows gas pollution grows severe with the increase of the gas box's volume or the decrease of gas flow rate.
- X-ray experiment confirms this rule very well.
- Self-sealed structure can improve the gas exchange speed in the MRPC chamber and has better performance against gas pollution.
- Further study on gas pollution can help us to reduce this effect in the design of CBM-TOF system.

Thank You!

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- Feb 22~26, 2016
- 13th RPC Workshop