Gaseous Ionization Detectors: Device Physics Simulations

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Outline

- Preamble
- Ionization detectors
- Device physics simulation
- Case studies
- Summary and outlook

The TEAM

- Deb Sankar Bhattacharya (IOP)
- Purba Bhattacharya (Weizzmann)
- Sudeb Bhattacharya (Retd)
- Jaydeep Dutta
- Abhik Jash
- Nayana Majumdar
- Supratik Mukhopadhyay
- Prasant Kumar Rout
- Mohammed Salim (AMU)
- Sandip Sarkar
- Muzamil Ahmad Teli (KU)
- Sridhar Tripathy

- The choice of topics is guided by our areas of interest
- An attempt will be made to present work done by other groups

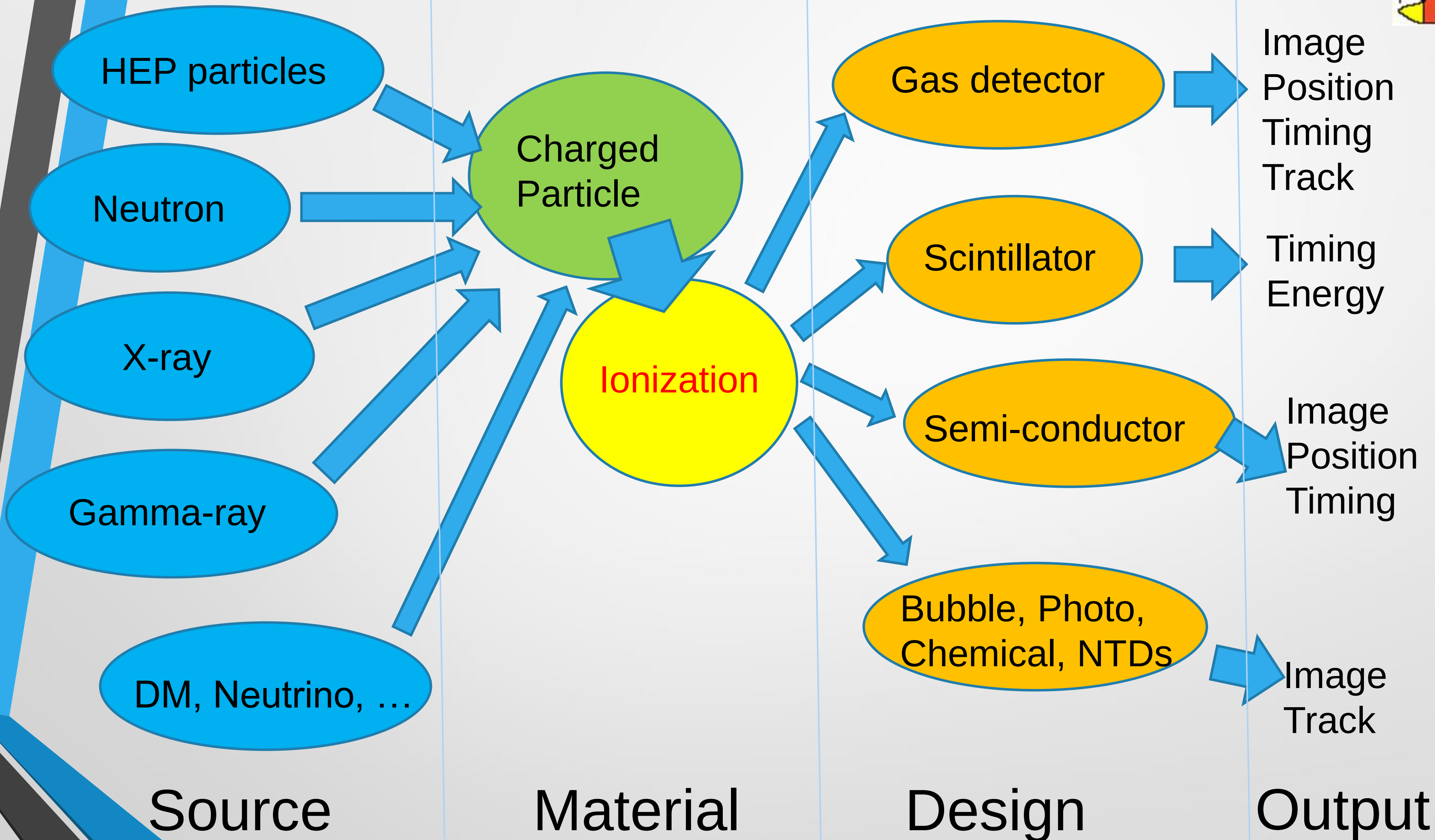
Areas of interest

- High energy physics experiments (INO, CMS, ALICE, ILC)
- Radiation imaging (Muon Tomography)
- Detector research and applications
- Development of improved algorithms

In a sense, all of the above are inter-connected.

I plan to provide a quick overview of our activities related to gaseous ionization detectors and corresponding simulation at the device level

(1) Preamble


HEP particles
Neutron
X-ray
Gamma-ray
DM, Neutrino, …
Charged Particle
Ionization
Gas detector
Scintillator
Semi-conductor
Bubble, Photo, Chemical, NTDs
Image
Position
Timing
Track
Timing
Energy
Image
Position
Timing
Image
Track
Source
Material
Design
Output

Detection goal

- **Goals**
  - Particle identification (mass, charge)
  - Energy (momentum)
  - Arrival direction
- **Observables**
  - Velocity
    - Time-Of-Flight, Cherenkov angle, Transition radiation
  - Energy loss
    - Bethe-Bloch
  - Total energy
    - Calorimeter

Detector Performance Parameters

Physics driven parameters:

- Momentum resolution is usually driven by spatial resolution and the strength of the magnetic field
- Velocity errors, depending on method used, would be driven by time resolution for TOF, by energy resolution for dE/dx energy loss measurement, spatial resolution for Cherenkov angle evaluation

Primary detector performance parameters:

- Gain, Time resolution, Spatial resolution, Energy resolution
- Detection efficiency
- Two-track spatial resolution
- Two-particle time resolution, rate capabilities

Other important considerations:

- Cost
- Stability in time, Lifetime
- Safety

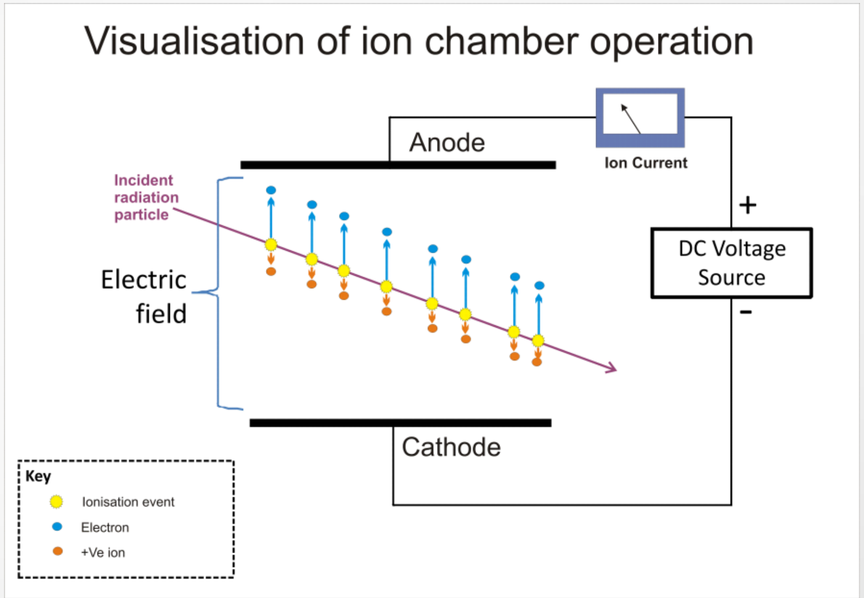
2. Ionization Detectors

Detectors that depend on ionization of the media and its registration

Gas / Liquid Detectors: Electron - Ion pairs
Geiger-Mueller counter, Proportional counter, Single / Multiple Wire chambers, Drift chambers, Time Projection Chambers, Resistive Plate Chambers, Micro-Pattern Gas Detectors

Solid State Detectors: Electron – Hole pairs
Silicon detectors, Diamond detectors

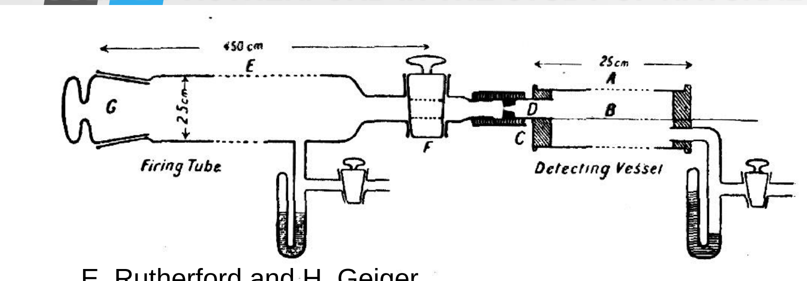
They can both be used as Tracking detectors in which you need to know the position to varied degrees of precision.



A particle passing through a gas-filled counter will ionize the gas along its path .The applied voltage V between the electrodes will sweep the positive and negative charges toward the respective electrodes causing a charge Q to be induced on readout electrodes.

Glorious tradition: 100 years of gaseous detector developments

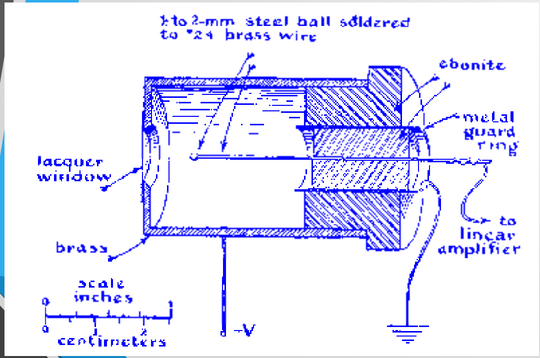
1908: FIRST WIRE COUNTER
USED BY RUTHERFORD IN THE STUDY OF NATURAL RADIOACTIVITY



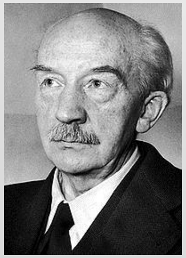
E. Rutherford and H. Geiger ,
Proc. Royal Soc. A81 (1908) 141

Nobel Prize in Chemistry in 1908

1928: GEIGER COUNTER
SINGLE ELECTRON SENSITIVITY

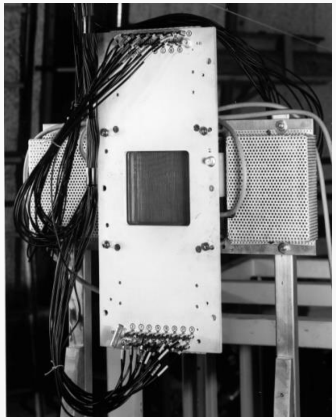


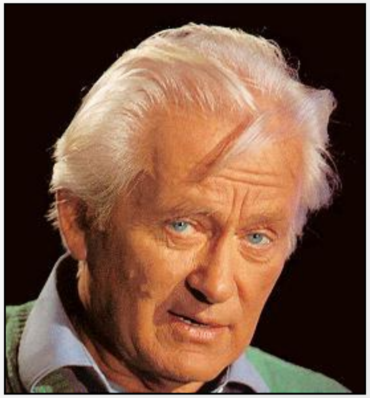
H. Geiger and W. Müller,
Phys. Zeits. 29 (1928) 839



Walther Bothe
Nobel Prize in 1954 for the "coincidence method"

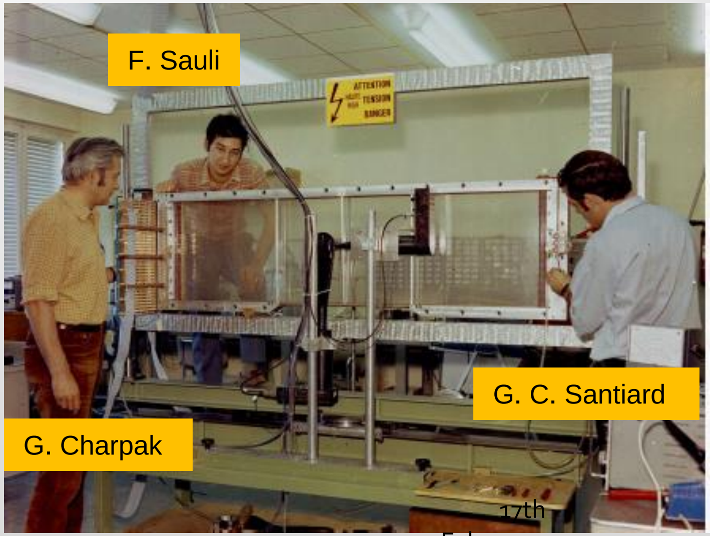
1968: MULTIWIRE PROPORTIONAL CHAMBER





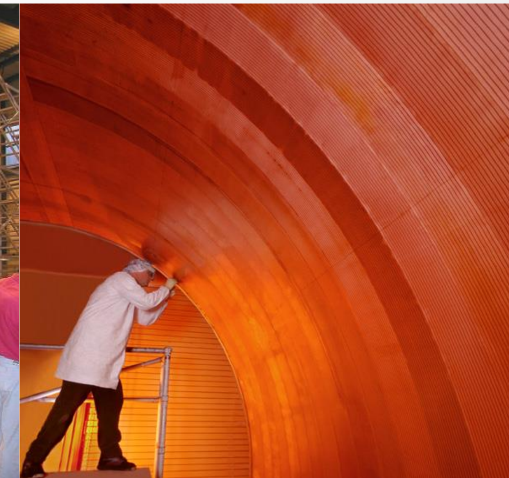
Nobel Prize in 1992

G. Charpak, Proc. Int. Symp. Nuclear Electronics
(Versailles 10-13 Sept 1968)

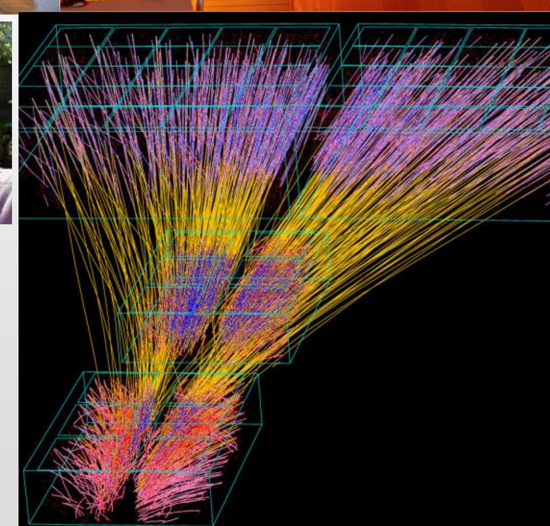


Variety of Gaseous Detectors

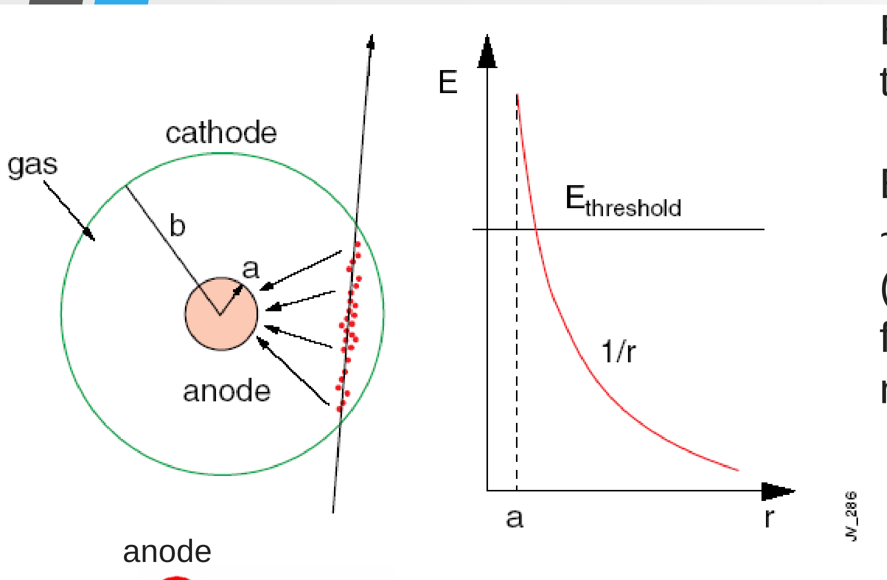
- Gas detectors advantages:
  - low radiation length
  - large areas at low price
  - flexible geometry
  - spatial, energy resolution …

- Huge popularity led to numerous incarnations
  - Resistive Plate Chamber
  - Time Projection Chamber
  - many more …

Single Wire Proportional Chamber



Electrons liberated by ionization drift towards the anode wire.

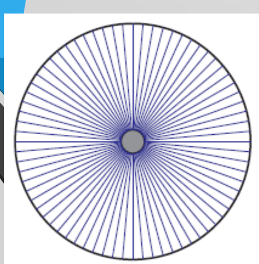
Electrical field close to the wire (typical wire Ø ~few tens of μm) is sufficiently high for electrons (above 10 kV/cm) to gain enough energy to ionize further → avalanche – exponential increase of number of electron ion pairs.

$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$

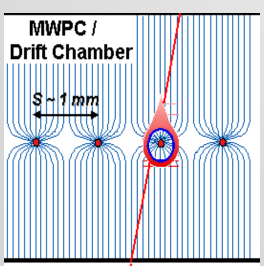
$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a}$$

C – capacitance/unit length

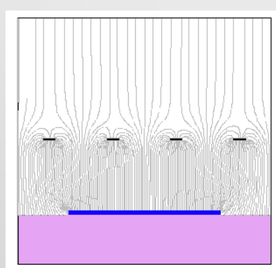
Cylindrical geometry is not the only one able to generate strong electric field:



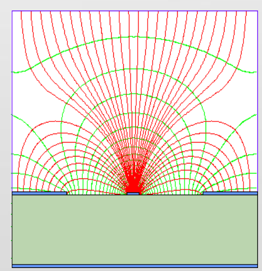
wire



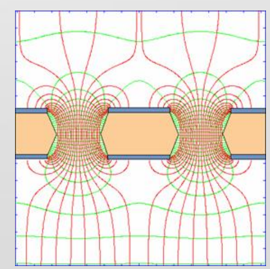
mwpc



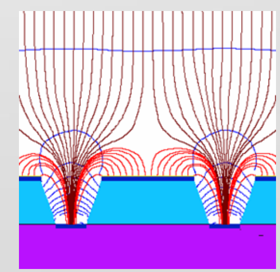
parallel plate



strip



hole



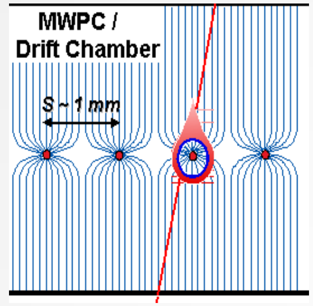
groove/well

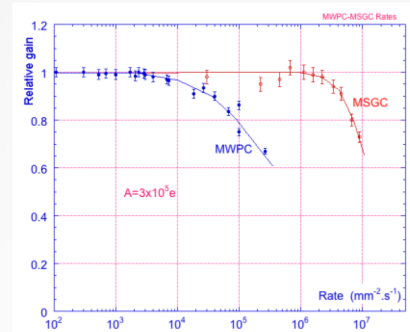
Micro-Pattern Gas Detectors

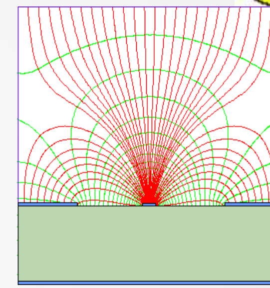
Printed Circuit Board (PCB) technology allowed micro-structures to be patterned In the 1990s

- Photolithography
- Etching
- Coating

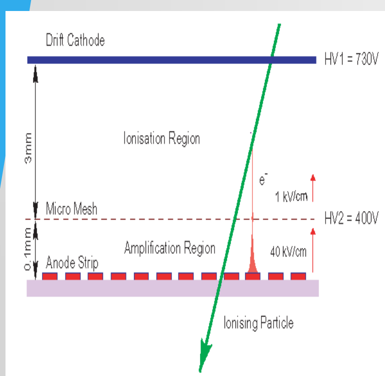
And later silicon wafer post-processing allowed to go further in small patterns

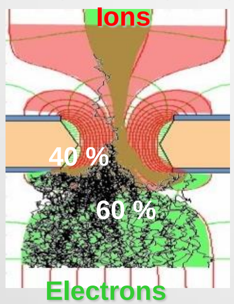


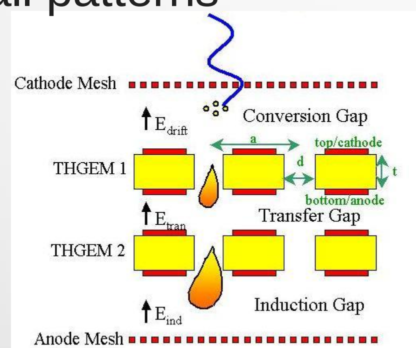


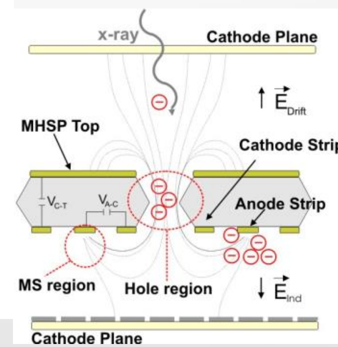


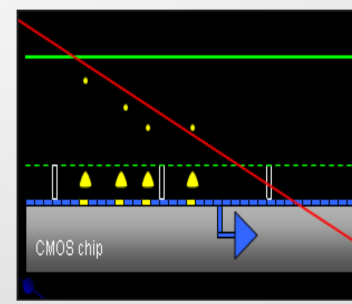
Rate Capability Comparison for MWPC and MSGC

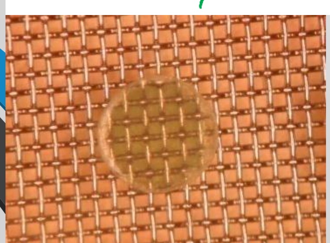




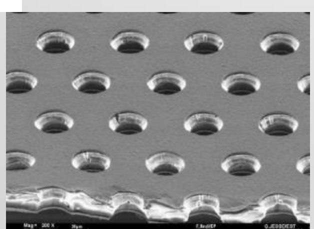




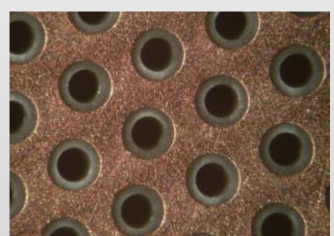




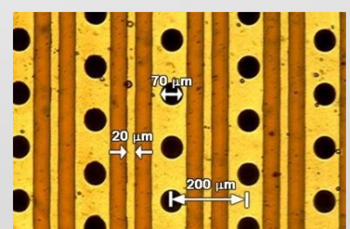
Micromegas



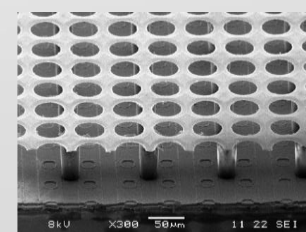
GEM



THGEM



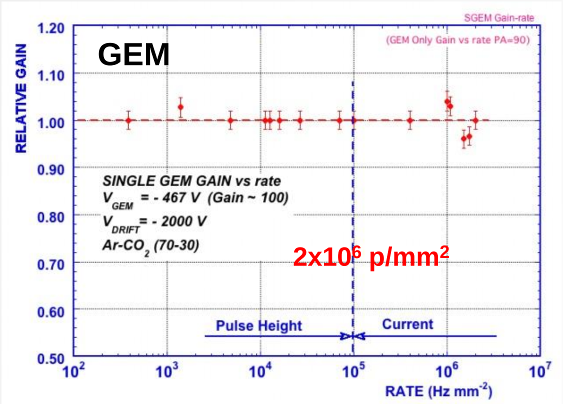
MHSP

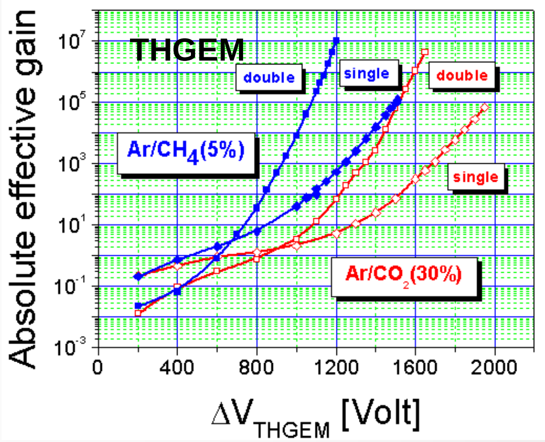


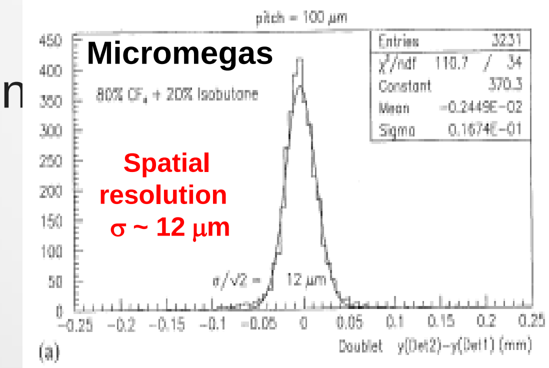
Ingrid

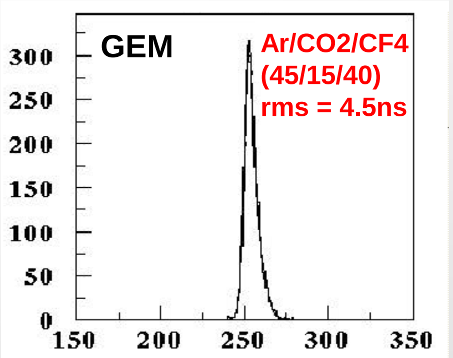
Micro-Pattern Gas Detectors Performance Summary

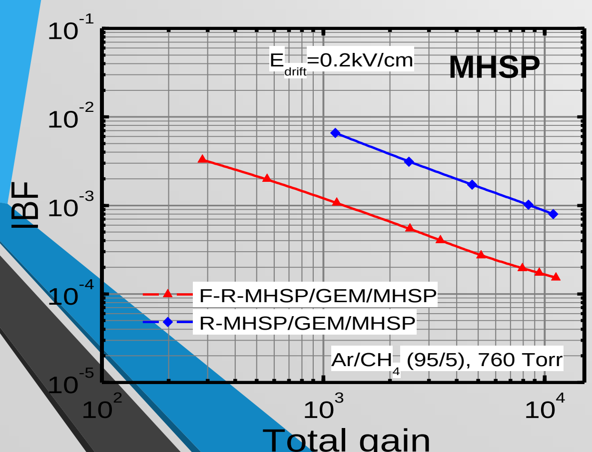
- Rate Capability
- High Gain
- Space Resolution
- Time Resolution
- Energy Resolution
- Ageing Properties
- Ion Backflow Reduction
- Photon Feedback Reduction
- Large size
- Less expensive

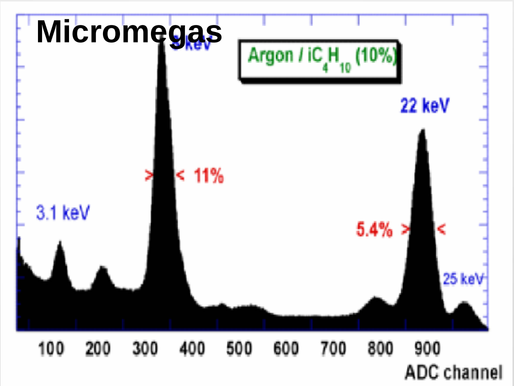


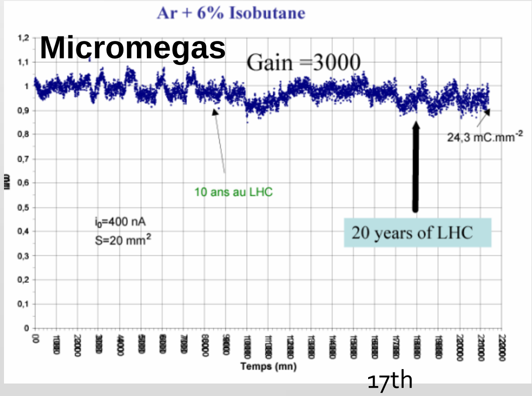












Gaseous Detector Issues

- Copious production of positive ions which are only slowly collected by the electrodes
  - Space charge distortion of electric field
  - Limited rate capability, especially in wire chambers

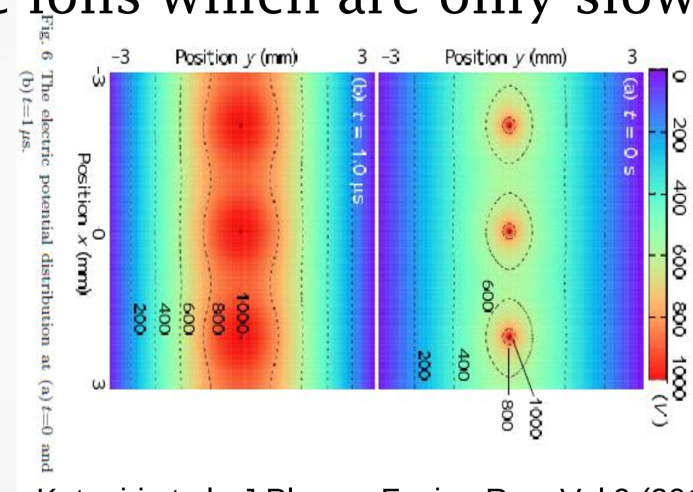
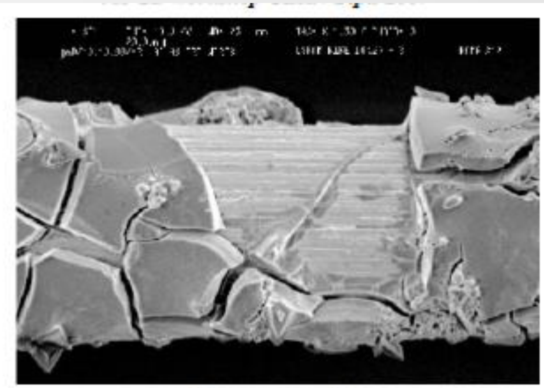


Fig. 6 The electric potential distribution at (a) t=0 and (b) t=1 µs.

Katagiri et al., J Plasma Fusion Res, Vol 9 (2010)

- Stability related
  - Wire instabilities in wire chambers
  - Limit to granularity
  - Charging up
  - Non-uniformity of operation
- Non-uniformities, asperities, imperfections in fabrication
  - Uncontrolled discharges
  - Permanent damage to the detector
- Polymerization and other ageing processe plasma chemistry
  - Deposition of thin electrode layer on electrodes
  - Deterioration of performance



A. Romaniuk et al, Nucl. Instr. and Meth. A515(2003)166 12

RD51 Collaboration

To advance technological development of Micropattern Gas Detectors

http://rd51-public.web.cern.ch/rd51-public/

- ~100 institutes
- ~ 500 people involved
- Representation (Europe, North America, Asia, South America, Africa)

Trieste, Italy, September 2015

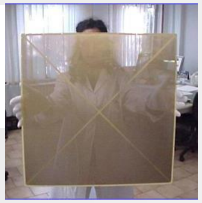
"RD51 aims at facilitating the development of advanced gas-avalanche detector technologies and associated electronic-readout systems, for applications in basic and applied research"

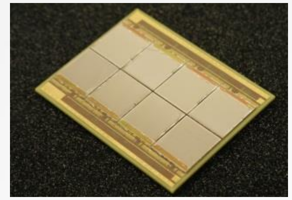
RD51 contributes to the LHC upgrades, BUT, the most important is:

RD51 serves as an access point to MPGD "know-how" for the world-wide community

RD51 Collaboration

Large Area Detectors
Assembly Optimization

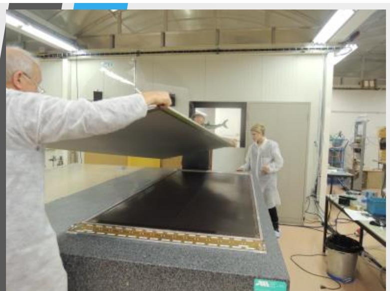


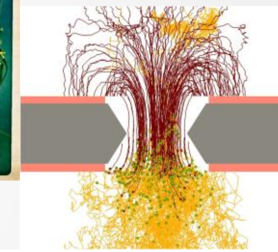


RD51 Common Projects
Generic R&D
Long Term Stability

WG1:

WG2:





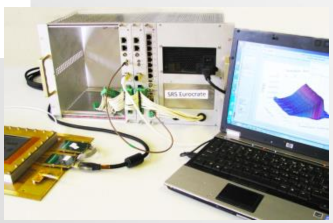
WG5:

MPGD
Electronics

RD51

Software Tools
and
Simulations

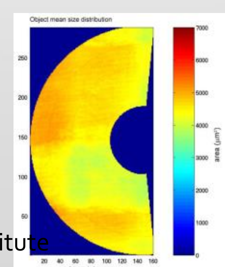
WG4:



WG7:

WG6:

Conferences, Meetings and Schools



CERN MPGD Workshop
Quality Control
and Industrialization

RD51 Common
Test Beam and Lab
Facilities

(3) Device Physics Simulation

why is it important, especially for MPGDs

- Insight
  - Optimization of experimental parameters, including environmental ones
  - Accurate interpretation of data
  - Better designs for future detectors

- Complications
  - Multiple aspects of complex physics and chemistry
  - Coexistence of large and small length-scales
  - Coexistence of large and small time-scales

MPGD Simulation Tools

- Focus on providing techniques for calculating **electron transport in small-scale structures**
- The main difference with traditional gas-based detectors is that **the electrode scale (~ 10 μm) is comparable to the mean free path between collisions**

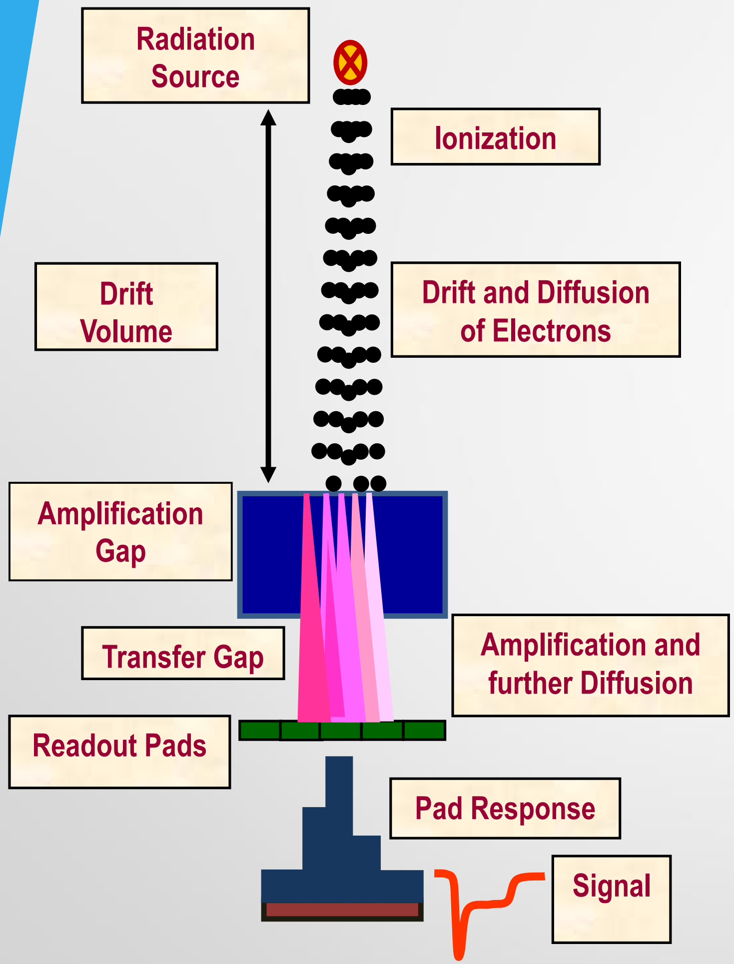
Development and Maintenance of Garfield++ (Fortran version Garfield is still available, but not actively supported):
Garfield++ is a collection of classes for the detailed simulation of small-scale detectors.

Garfield++ and Garfield contains:
- electron and photon transport using cross sections provided by Magboltz
- ionization processes in gases, provided by Heed and MIP
- ionization and electron transport in semi-conductors
- field calculations from finite elements, boundary elements, analytic methods

Simulation Improvements:
Transport:
- ion mobility and diffusion, measurement and modeling
- ongoing update of electron cross sections
- e-ion recombination process in Xe
- thermal motion

Photons:
- update in UV emission
- inclusion of IR production
- photon trapping and resulting excitation transport
- photon absorption in the gas (gas feedback)
- photon absorption in and electron emission from walls (feedback)
- photo cathodes

Detector and its simulation



Simulation steps

- **(1) Ionization:** energy loss through ionization of a particle crossing the gas and production of clusters – **HEED / MIP**
- **(2) Transport and Amplification:** electron drift velocity and the longitudinal and transverse diffusion coefficients - **MAGBOLTZ**
- **(3) Detector Response:** Charge Induction using Reciprocity theorem (Shockley-Ramo's theorem), Particle drift, charge sharing (pad response function - PRF); Charge Collection - **GARFIELD**
- **Signal generation and acquisition: SPICE**
- **Electromagnetic field:** Except ionization, each step depends critically on physical / weighting electric field and magnetic field, if present (**Analytic / ANSYS / COMSOL / neBEM / Elmer-Gmsh etc**).

Field solving is especially critical for MPGDs, due to their intricate, essentially 3D geometry.

Different approaches to simulation

- Geant4 / FLUKA / SRIM look at the larger picture
  - Important, without doubt

- Device physics simulation
  - Analytic
  - Semi-analytic / lumped element (Circuit) simulation
  - Two-dimensional (Garfield analytic)
  - Three-dimensional (Garfield, Garfield++)

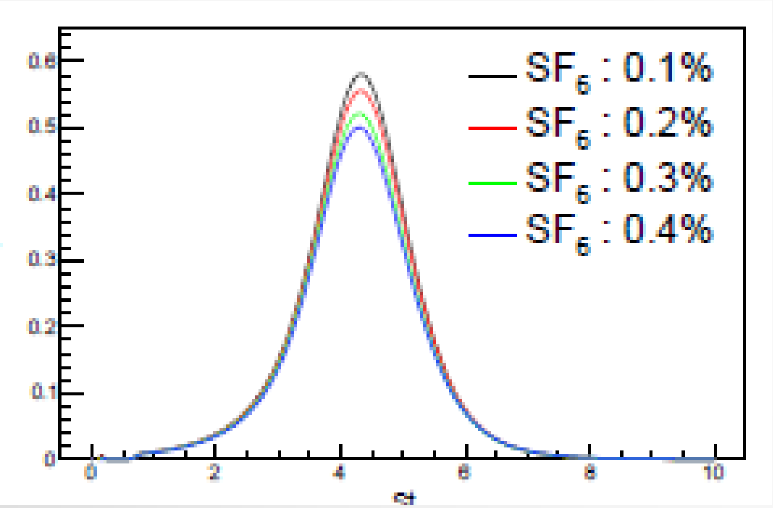
Analytic approach for Time resolution

- Assuming,
  - (i) an average number of n_0 efficient clusters which fluctuate according to Poisson distribution,
  - (ii) a cluster size distribution $f\,(m)$ with Z-transform $F(z)$ with a radius of convergence r_F ,
  - (iii) avalanche multiplication according to Legler's avalanche model and
  - (iv) a threshold of n electrons, the time response function for an RPC

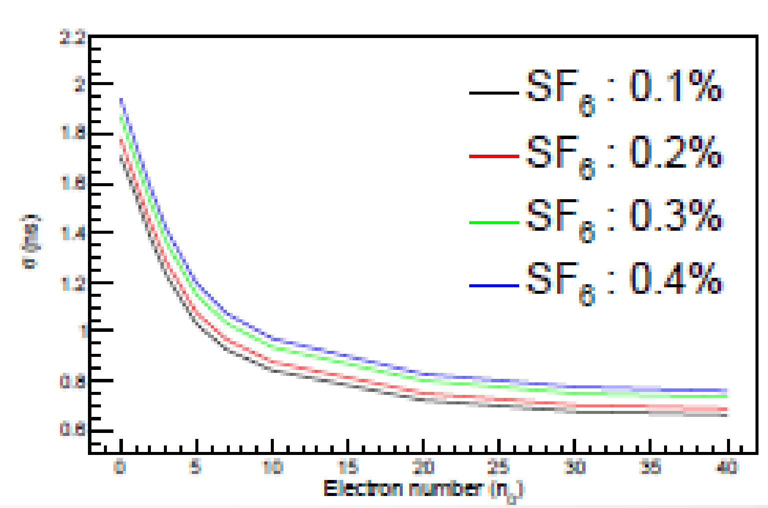
$$\rho(n,t) = \frac{1}{2\pi i}\oint \frac{e^{n_0F(z)-1}}{e^{n_0}-e^{n_0F(1/k)}}\,\frac{(1-k^2)nS}{(1-kz)^2}\,e^{-St-n\frac{(1-k)(1-z)}{1-kz}e^{-St}}\,dz$$

Well, the procedure is not entirely analytic …
The evaluation is numerical and n_0 is obtained using another code called HEED.
However, the essence remains analytic …

Time response and resolution



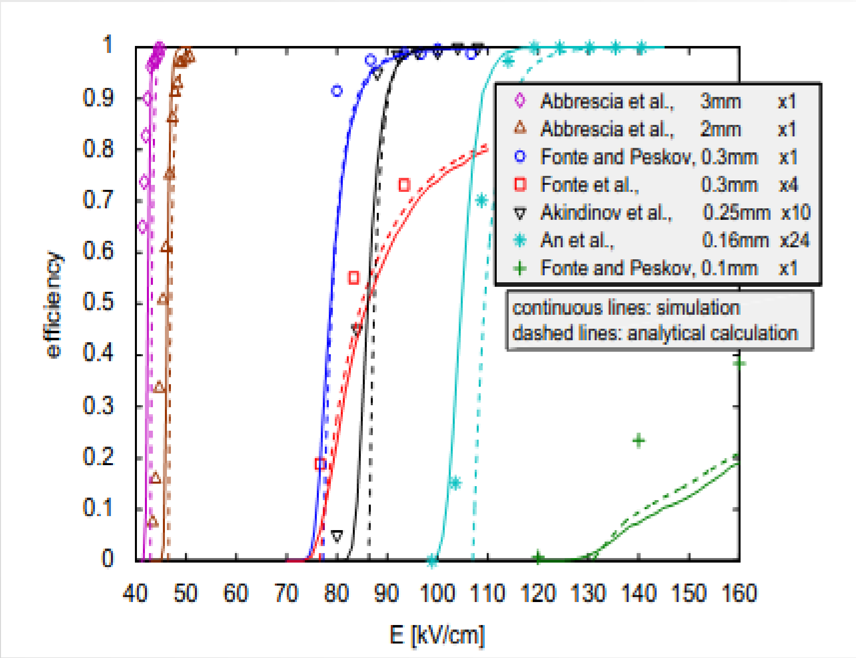
(a)



(b)

(a) Time response function for different gas mixtures in 2 mm gap RPCs, n = 1000 and n0 = 5 and
(b) Time Resolution for different gas mixtures.

Semi-Analytic Approach



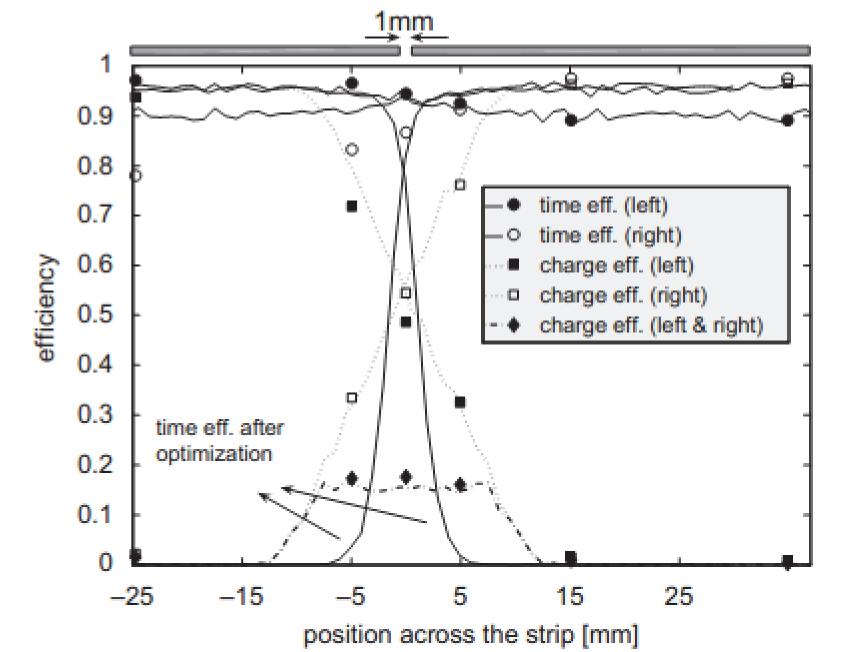


Fig. 6. Measured time (∘) and charge (□, ◇) efficiency as a function of the position across the strip according to Ref. [17]. Lines show simulations for $Q_{th}=20$ fC, $HV=5.8$ kV ($\hat{F}_{ct}=51\%$). The time efficiency for an optimized structure at $Q_{th}=40$ fC and $HV=6.0$ kV ($\hat{F}_{ct}=7.2\%$), assuming ideal position reconstruction, is indicated with arrows.

Simulation of resistive plate chambers with multi-strip readout
D. Gonzalez-Dia, NIM A 661 (2012) S172–S176

Charge Spectra

Heed + Magboltz + neBEM + dedicated MC

Gas Mixture ($C_2H_2F_4/C_4H_{10}/SF_6$)	Charge(CRO) (pC)	Charge(DAQ) (pC)	Simulated Charge (at 3.6 KV/mm in fC)	Simulated Charge (at 5kV/mm in pC)
95.1/4.5/0.4	0.51	0.19	0.11	14.06
95.2/4.5/0.3	0.66	0.27	0.16	15.45
95.3/4.5/0.2	0.85	0.35	0.99	16.07
95.4/4.5/0.1	1.29	0.57	0.96	18.15

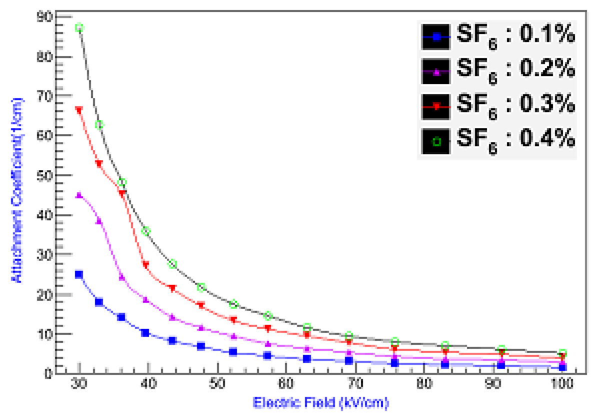


Figure 6: Attachment coefficient (α).

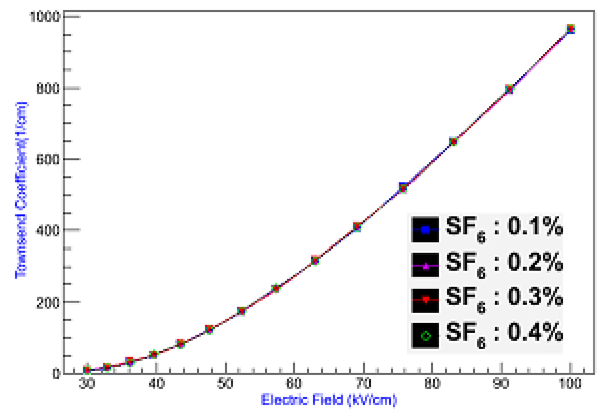
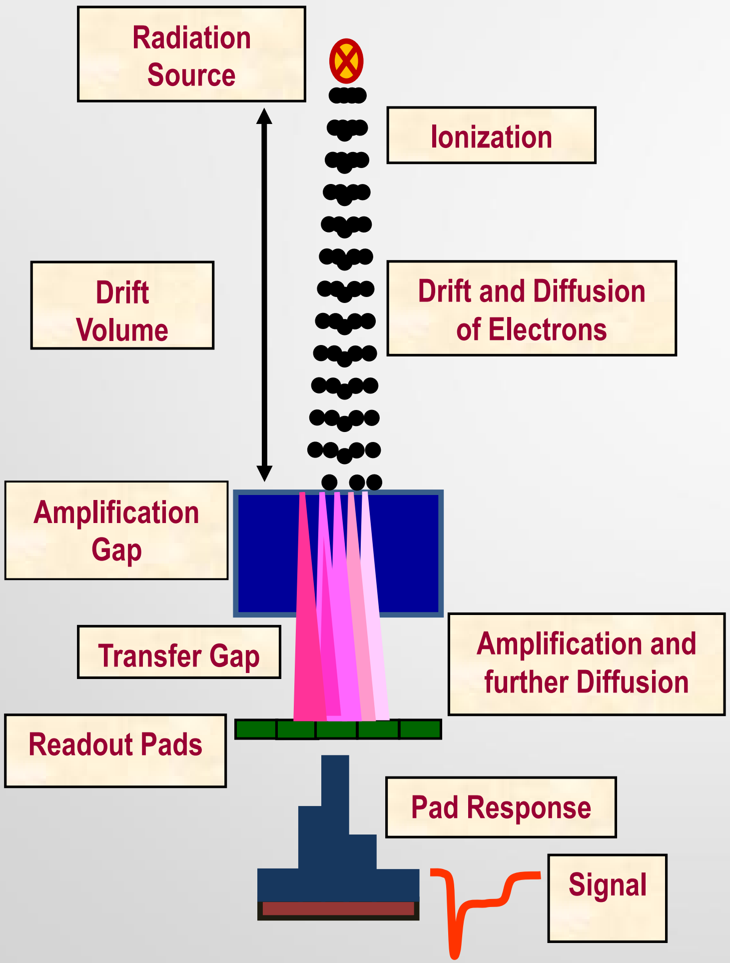


Figure 7: Townsend coefficient (η).

Simulation studies on the Effect of SF6 in the RPC gas mixture, M Salim et al.

Detailed device simulation



(1) **Ionization:** energy loss through ionization of a particle crossing the gas and production of clusters

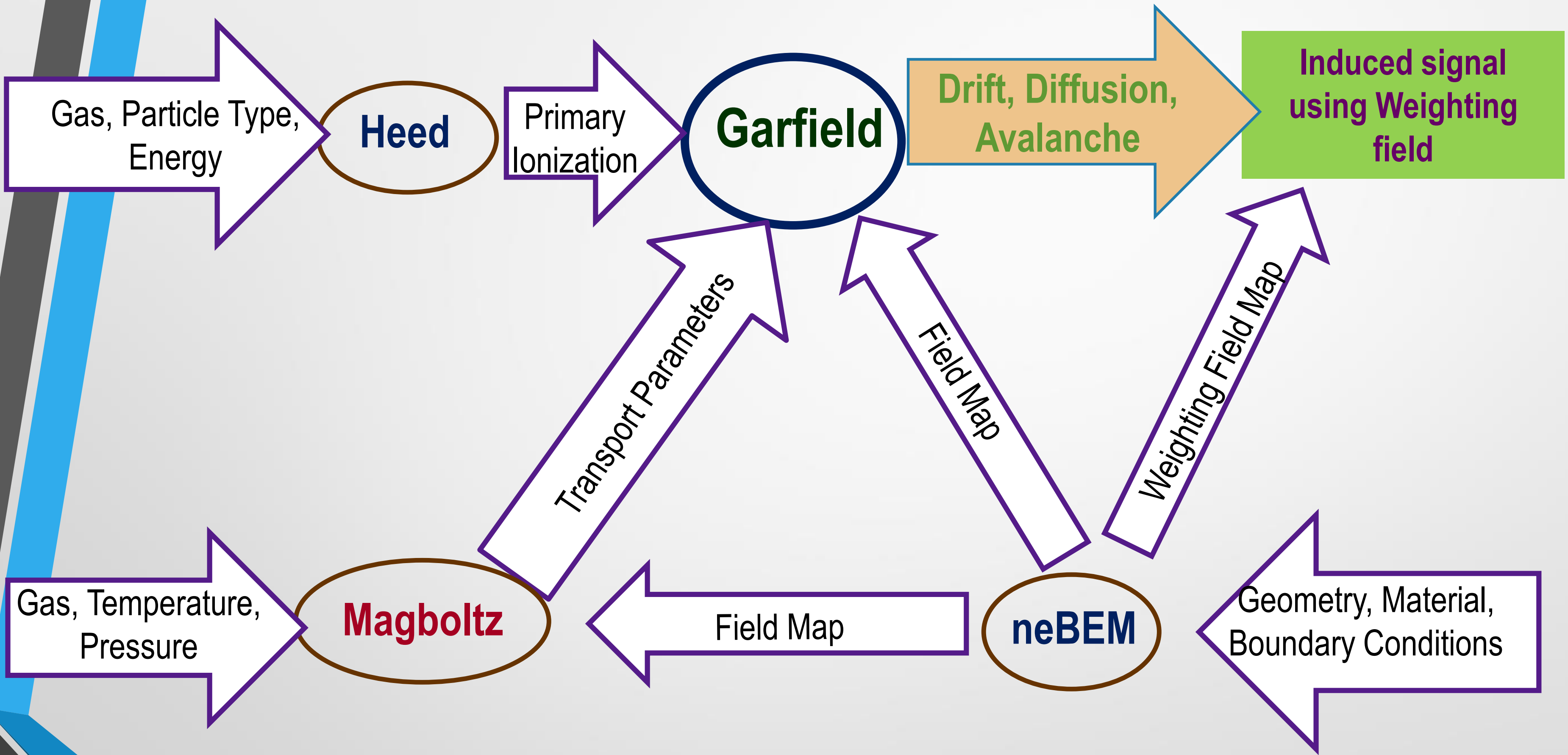
(2) For a specified Electromagnetic field:

- **Transport and Amplification:** electron drift velocity and the longitudinal and transverse diffusion coefficients
- **Detector Response:** Charge Induction using Reciprocity theorem (Shockley-Ramo's theorem), Particle drift, charge sharing (pad response function - PRF); Charge Collection

➢ **Signal generation and acquisition**

➢ **Electromagnetic field:** Except ionization, each step depends critically on physical / weighting electric field and magnetic field, if present

RD51 simulation framework



neBEM is yet to be interfaced to Garfield++

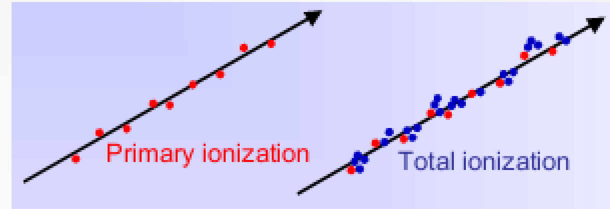
(1) Ionization using HEED

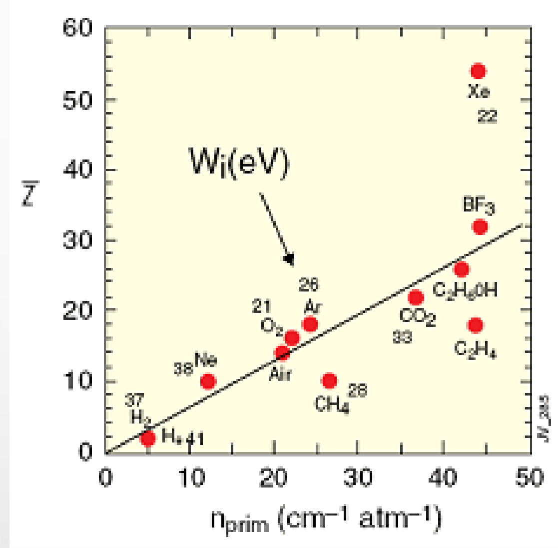
Primary ionization, n_p
Secondary ionization, n_s (due to δ-electrons)
Total ionization, $n_T = n_p + n_s$

$n_T = \Delta E / W_i = (dE/dx)\, L / W_i$
$n_T = 3 \ldots 4\, n_p$

where
ΔE = total energy loss
L = thickness of medium
W_i = effective energy loss / pair

Which gas would be suitable ?
(1)easily ionisable; (2)not attaching: doesn't swallow electrons; (3)neither flammable, nor explosive, nor toxic; (4)discharge resistant; (5)affordable.

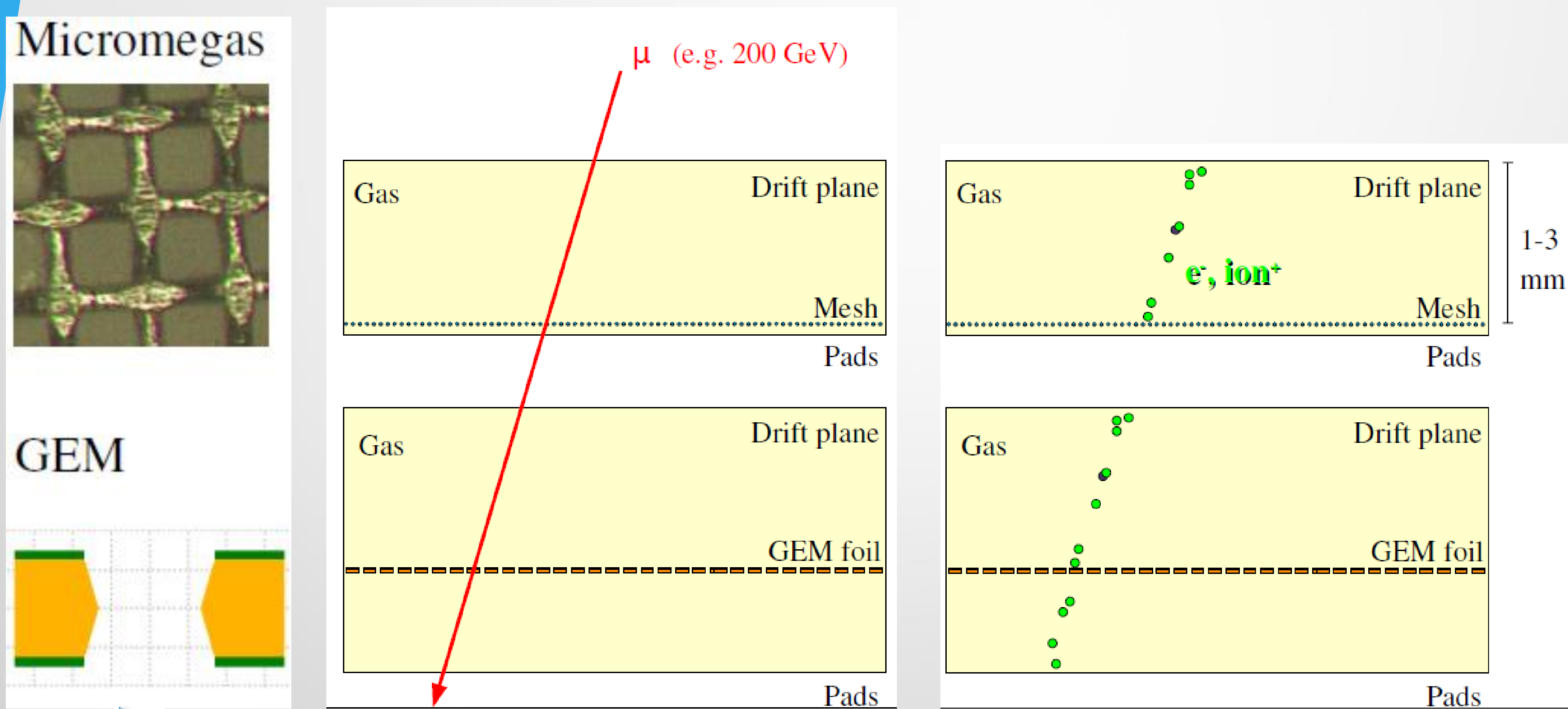




Common choice: Noble gas with an admixture of molecular gas called quencher.

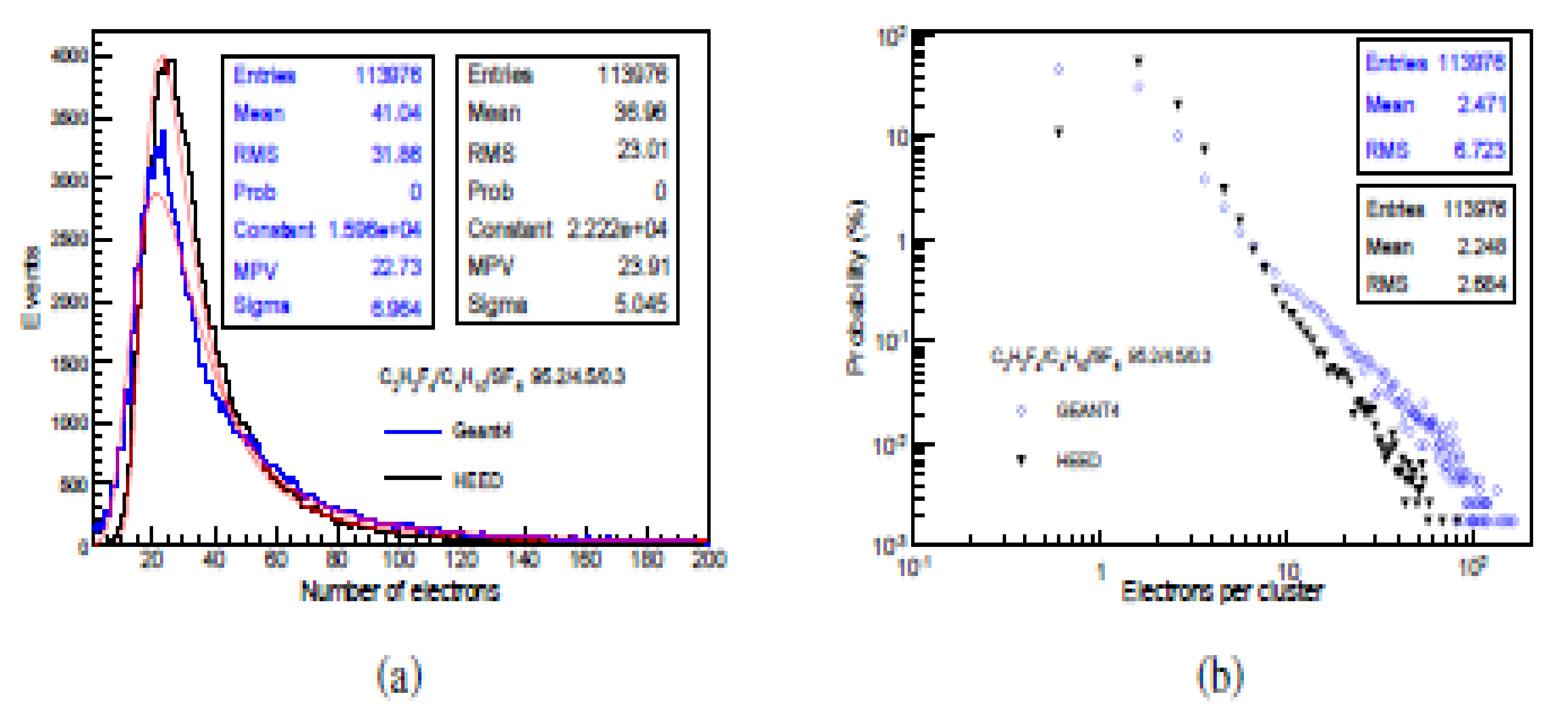
Argon and CO_2 can be an option, as already observed in many presentations

Primary ionization



- Heed: Igor Smirnov, *Modeling of ionization produced by fast charged particles in gases,* accepted for publication in NIM (Aug 2005).

Comparison between Geant4 and HEED



(a) Electron distribution in gas mixtures *C*2*H*2*F*4/*C*4*H*10/*SF*6 in the proportion 95.2:4.5:0.3 ,the red lines represent the landau fit. and (b) Cluster size distribution, when a muon of energy 4 GeV passed through the RPC chamber kept at T= 20◦C and P=760 Torr.

(2) Field Solver Possibilities

Solve Poisson's equation

$$\nabla.(m\nabla P) = S$$

BEM

- ✓ Reduced dimension
- ✓ Accurate for both potential and its gradient

- x Complex numerics
- x Numerical boundary layer
- x Numerical and physical singularities

Analytic

- ✓ Exact
- ✓ Simple interpretation

- x Restricted
- x 2D geometry
- x Small set of geometries

FEM / FDM

- ✓ Nearly arbitrary geometry
- ✓ Flexible

- x Interpolation using shape functions for non-nodal points
- x Solves for potentials and fields are relatively poorly represented
- x Difficulty in unbounded domains

Finite Element Basics

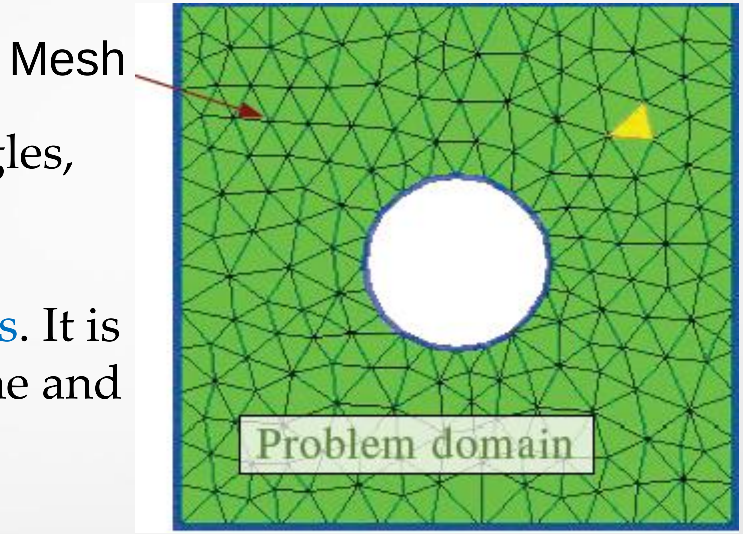
A mesh subdivides the problem domain into elements.

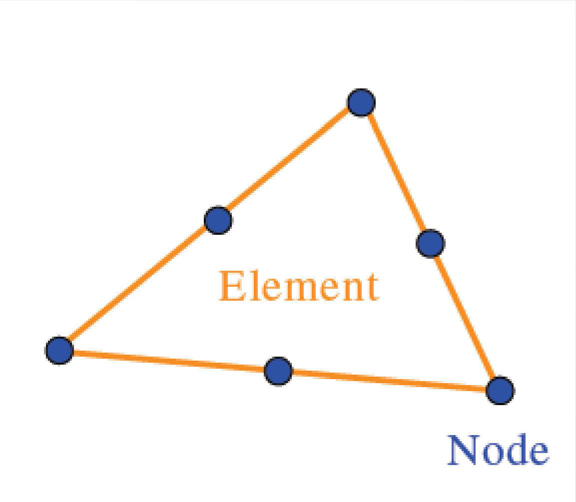
Elements are simple geometric shapes: triangles, squares, tetrahedra, hexahedra etc.

Important points of elements are called nodes. It is usual that several elements have a node at one and the same location.

Each node has its own shape function $N_i(r)$: continuous functions (usually polynomial), defined only throughout the body of the element

The solution of a finite element problem is given in the form of potential values at each of the nodes of each of the elements: v_i.
At interior points of an element: $V(r) = \sum v_i N_i(r)$





Solution of 3D Poisson's Equation using BEM

- Numerical implementation of boundary integral equations (BIE) based on Green's function by discretization of boundary.
- Boundary elements endowed with distribution of sources, doublets, dipoles, vortices.

Electrostatics BIE

$$\Phi(\vec{r}) = \int_S G(\vec{r},\vec{r}')\rho(\vec{r}')dS'$$

Potential at r

Charge density at r'

Green's function

$$G(\vec{r},\vec{r}') = \frac{1}{4\pi\varepsilon\left|\vec{r}-\vec{r}'\right|}$$

ε - permittivity of medium

discretization

$$[A]\{\rho\}=\{\Phi\}$$

Influence Coefficient Matrix

$$\{\rho\} = [A]^{-1}\{\Phi\}$$

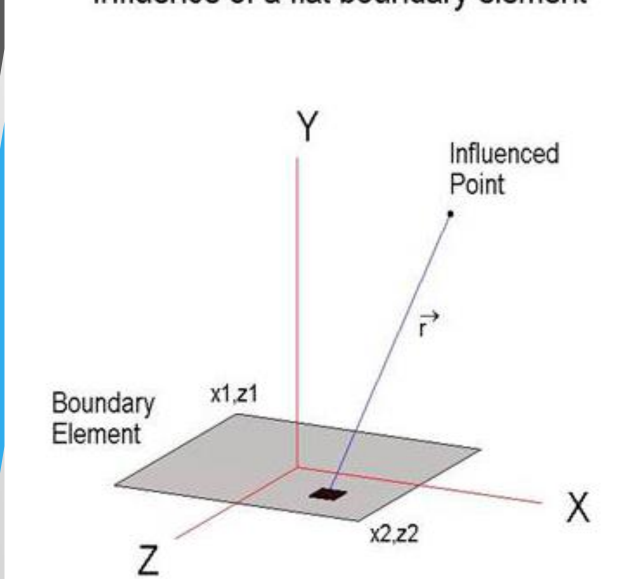
Accuracy depends critically on the estimation of [A], in turn, the integration of G, which involves singularities when r → r'.

Most BEM solvers fail here.

Foundation expressions of ISLES

Inverse Square Law Exact Solutions

Rectangular element



$$\Phi(X,Y,Z)=\int_{x1}^{x2}\int_{z1}^{z2}\frac{dxdz}{\sqrt{(X-x)^2+(Y-y)^2+(Z-z)^2}}$$

Value of multiple dependent on strength of source and other physical consideration

$$\Phi(X,Y,Z)=$$

$$\frac{1}{2}\times\left\{\begin{array}{l} 2\times(X\,|\,Z\,|\,x_i\,|\,z_j)\times\ln\left(\dfrac{D_{i,j}-(X\,|\,Z-x_i\,|\,z_j)}{D_{m,n}-(X\,|\,Z-x_m\,|\,z_n)}\right) \\ +iS_j|Y|\times\left[\tanh^{-1}\left(\dfrac{R_j-iI_i}{D_{i,j}|Z-z_j|}\right)-\tanh^{-1}\left(\dfrac{R_j+iI_i}{D_{i,j}|Z-z_j|}\right)\right]\end{array}\right\}-2\pi Y$$

4 log terms

4+4 complex $\tanh^{-1}$ terms

$$D_{i,j}=\sqrt{(X-x_i)^2+Y^2+(Z-z_j)^2}$$

$$R_i=Y^2+(Z-z_i)^2$$

$$I_i=(X-x_i)|Y|$$

$$S_i=Sign(Z-z_i)$$

May need translation and vector rotation

nearly exact Boundary Element Method (neBEM)

A new formulation based on green's function that allows the use of exact close-form analytic expressions while solving 3d problems governed by Poisson's equation. It is very precise even in critical near-field regions, and microscopic length scale.

It is easy to use, interface and integrate neBEM

Stand-alone
A driver routine
An interface routine
Post-processing, if necessary

Garfield
Garfield prompt
Garfield script

Charge density at all the interfaces

Potential at any arbitrary point

Field at any arbitrary point

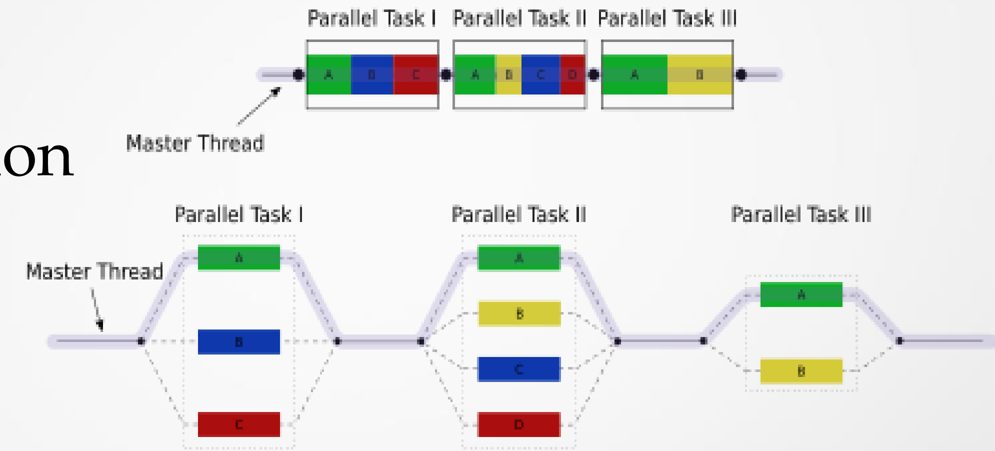
Capacitance, forces on device components properties can be obtained by post-processing

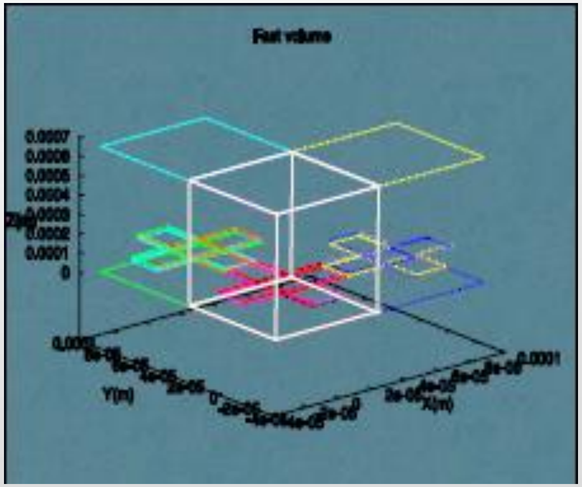
neBEM@CERN

http://nebem.web.cern.ch

Code Parallelization, Fast Volume, Adaptive Modelling

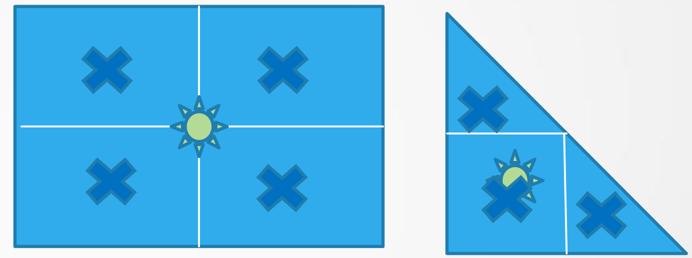
- Open Multi-Processing (OpenMP): an Application Programming Interface (API).
- Fast volume for both physical and weighting field
- Adaptive modelling

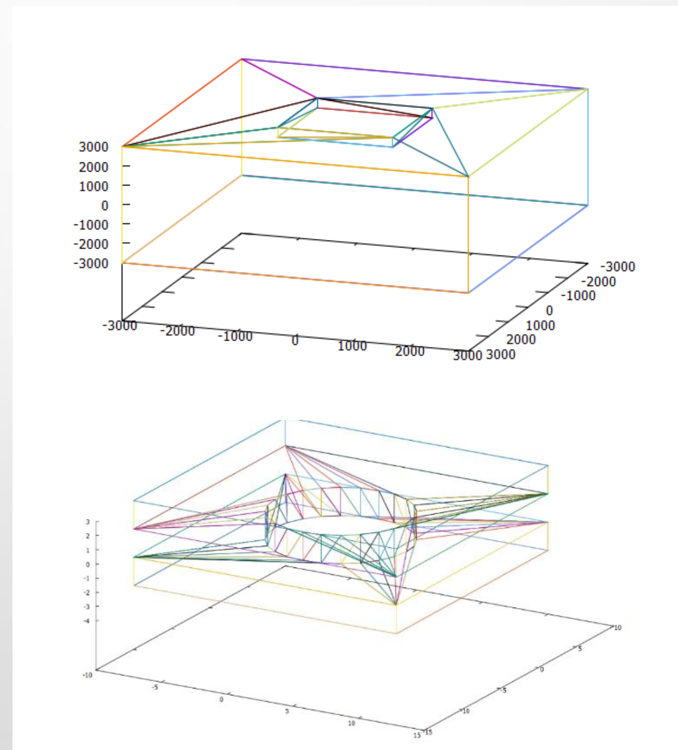




neBEM recent developments

- Error estimation: boundary condition being evaluated at non collocation points (OptEstimateError; can lead to effective adaptive meshing)
- Charging up: electrons and ions are being assigned to elements on which they get deposited (OptChargingUp)
- Space charge: basics are ready
- Interface to Garfield++: simple approach being implemented
- Geometry modeler: Geant4 approach
- Charge dispersion, in slow progress





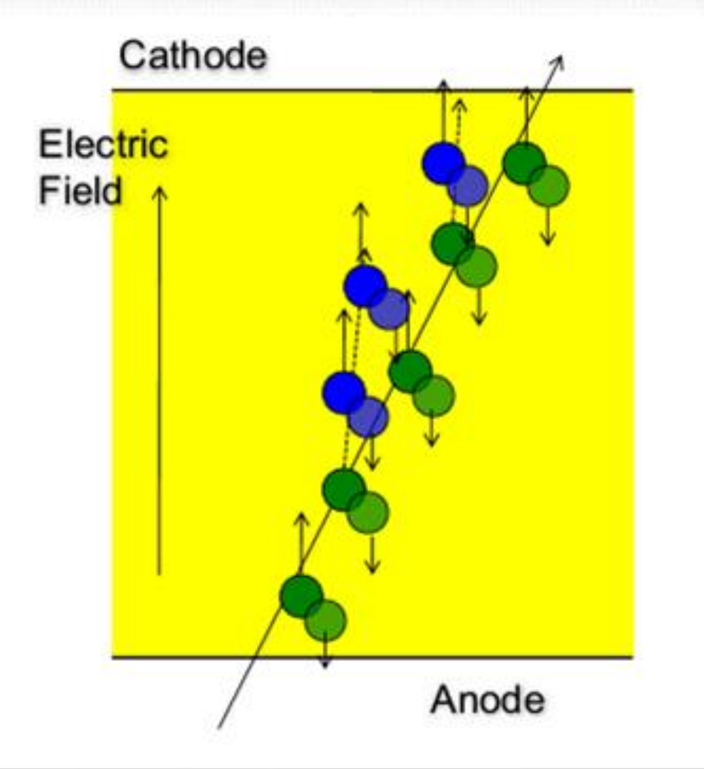
(3) Transport, Interaction, Multiplication using MagBoltz

Charges created near the track

Without electric field, there is only thermal diffusion

Electric field accelerates charges which, in turn, loses energy through interactions with gas

Electrons drift towards anode and positive ions move towards cathode

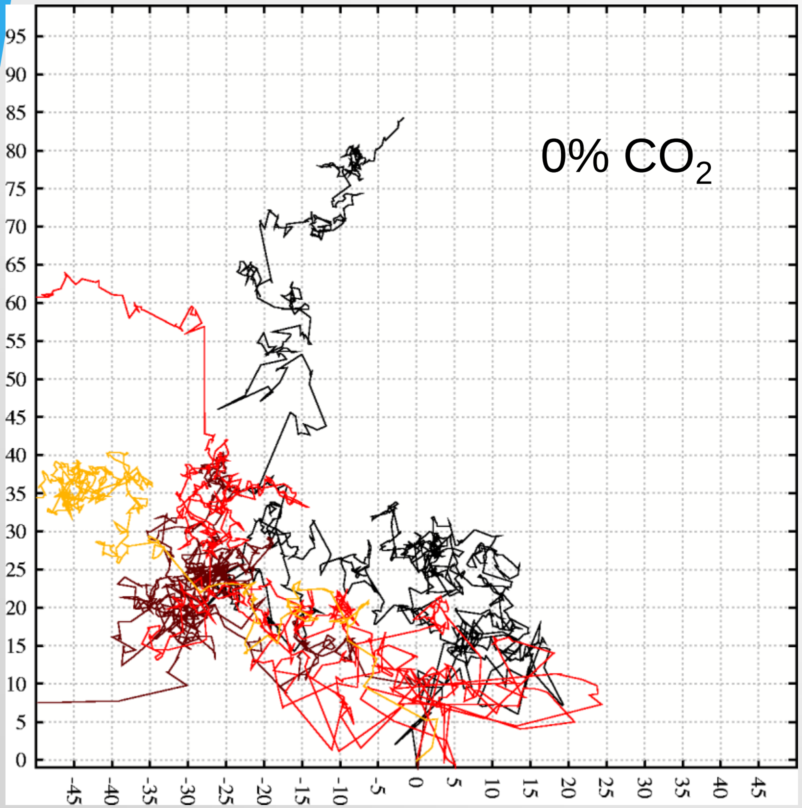


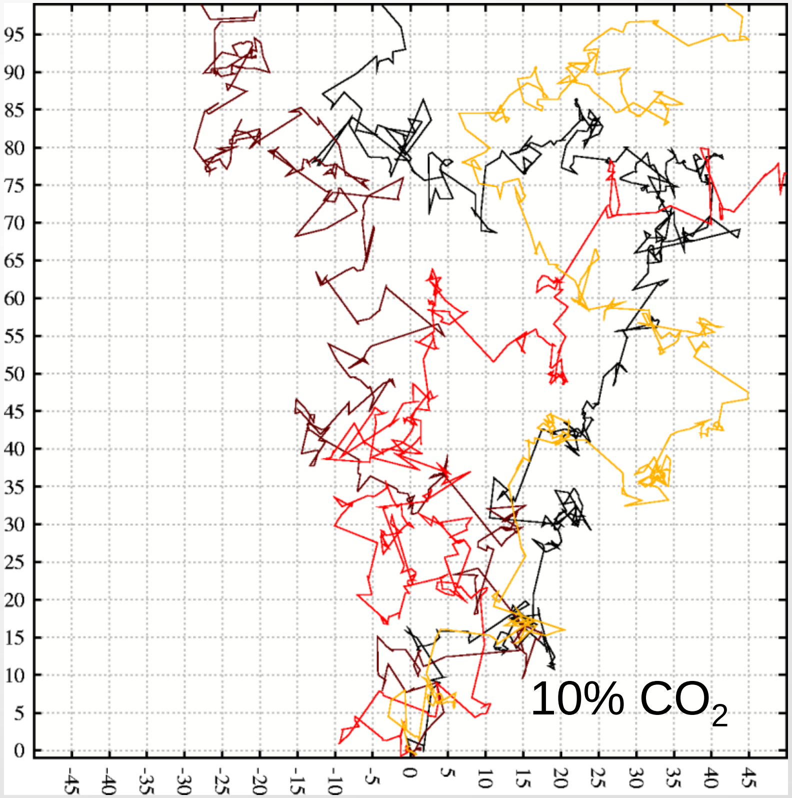
Which gas would be suitable ?
(1)easily ionisable; (2)not attaching: doesn't swallow electrons; (3)neither flammable, nor explosive, nor toxic; (4)discharge resistant; (5)affordable.

Maxwell-Boltzmann Transport

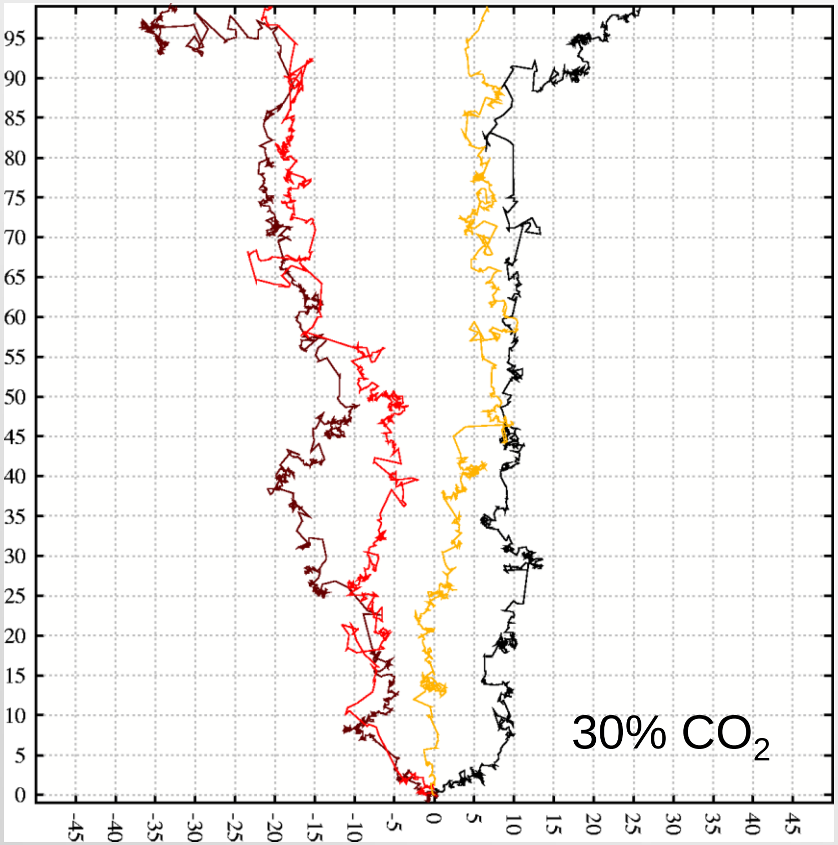
- The MAGBOLTZ program computes drift gas properties by "numerically integrating the Boltzmann transport equation" - *i.e.*, simulating an electron bouncing around inside a gas. By tracking how far the virtual electron propagates, the program can compute the drift velocity. By including a magnetic field, the program can also calculate the Lorentz angle. It can just as easily compute transverse diffusion coefficients, electron mobilities and other parameters.
- In order to find macroscopic parameters like the drift velocity, MAGBOLTZ needs to know about the microscopic nature of each gas under study. The most important quantities are the scattering cross sections, which measure how likely collisions are to occur, and the energy loss per collision.
- Steve Biagi, NIM A 421 (1999) 234-240

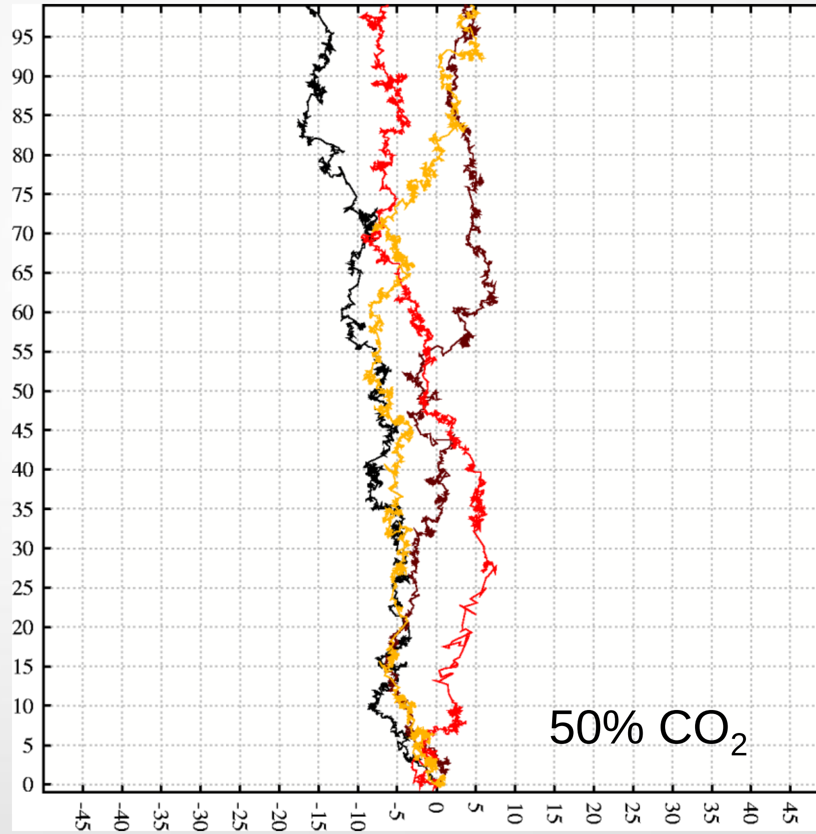
Electrons in Ar/CO_2 at E = 1 kV/cm





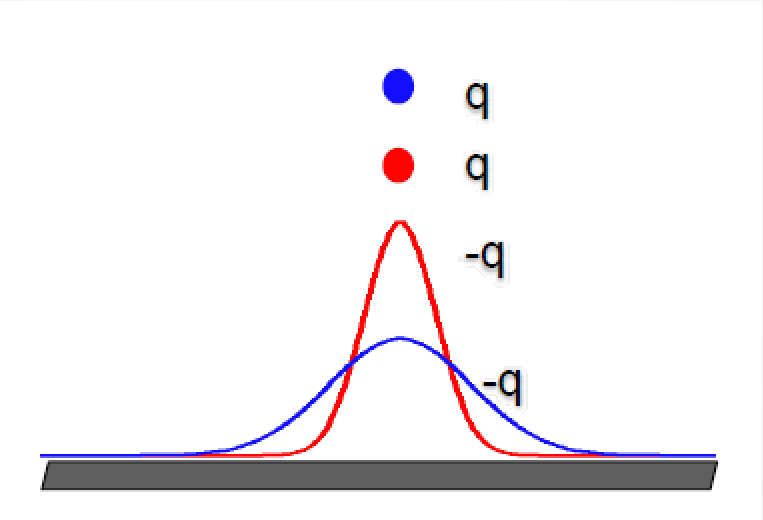
Electrons in Ar/CO_2 at E = 1 kV/cm



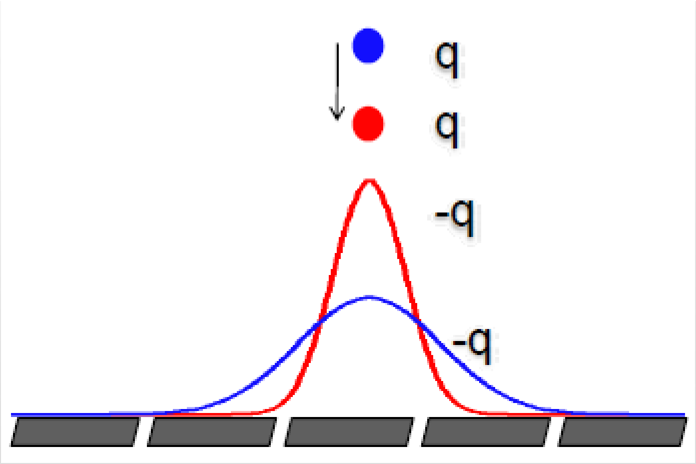


(4) Garfield for all other processes, upto Signal Generation

On a continuous grounded metal plate
Different charge positions induce different charge distributions but the total charge induced remain the same.



On a segmented grounded metal plate
The surface charge density remains same as above
The charge on each strip changes with change in charge position
Current flows between a strip and the ground, if the charge is moving



Detector Response

Current induced in an electrode is:

- Proportional to the charge q
- Proportional to the velocity of the charge $\mathbf{v_d}$
- Dependent on the electrode and the geometry

The induced current can be shown to be

$$I = -q\, \mathbf{v_d} \cdot \mathbf{E_w}$$

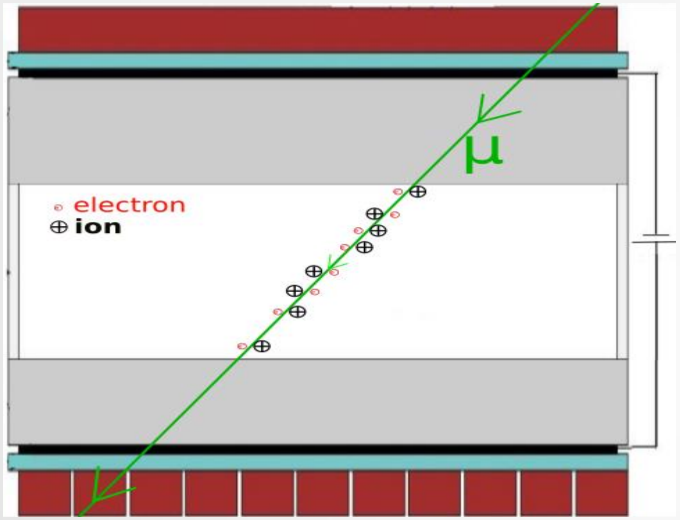
The geometry information is in $\mathbf{E_w}$, the weighting field. Each electrode has its own weighting field.

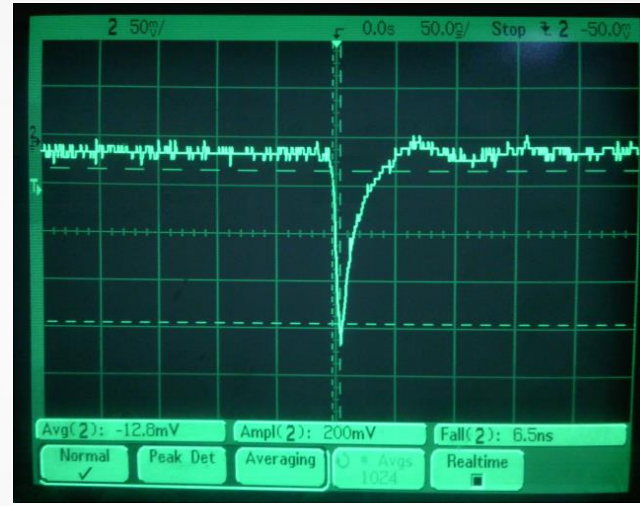
Computation of weighting field:

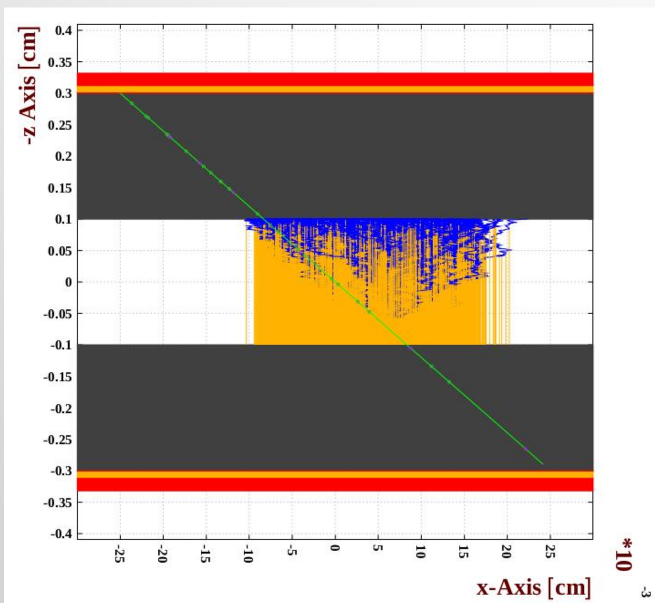
(Green's Reciprocity theorem, Shockley-Ramo theorem)

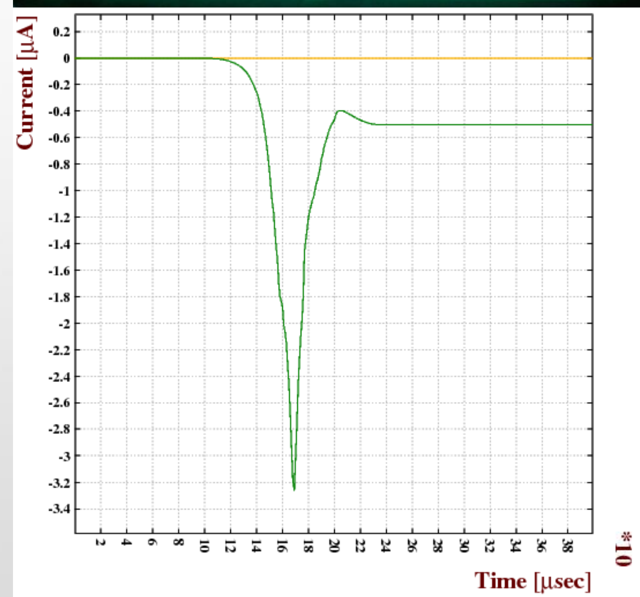
- Read-out electrode set to 1
- All other electrodes set to 0

Avalanche and signal induction





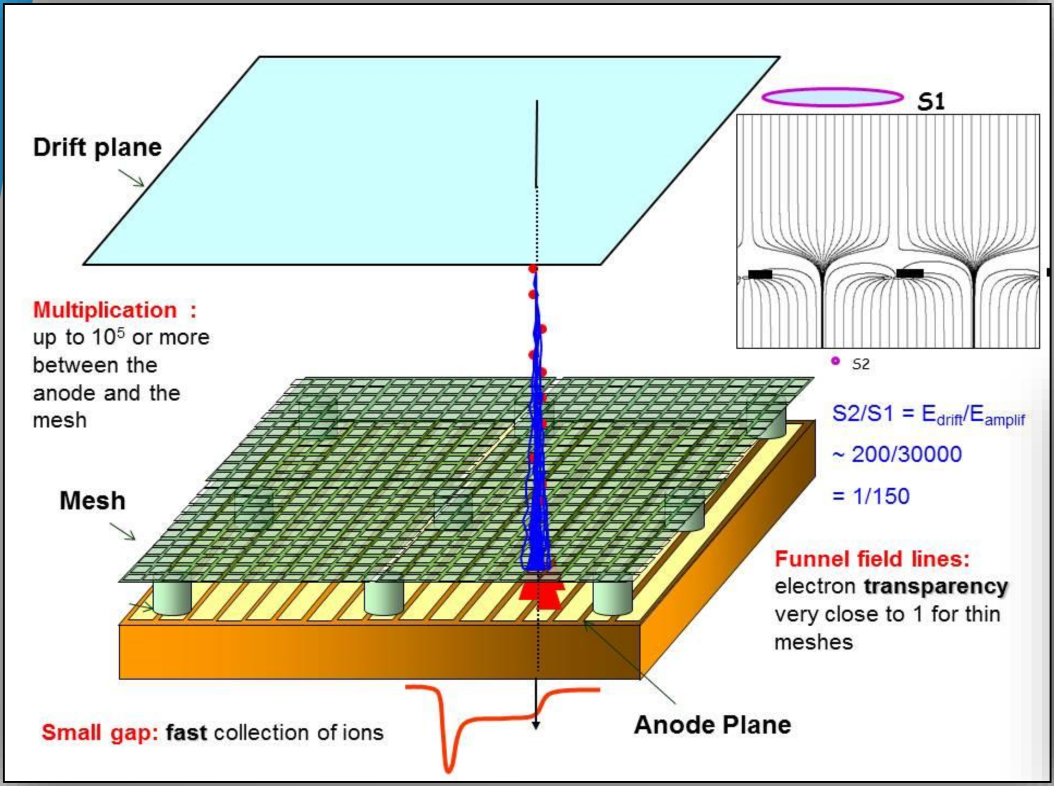


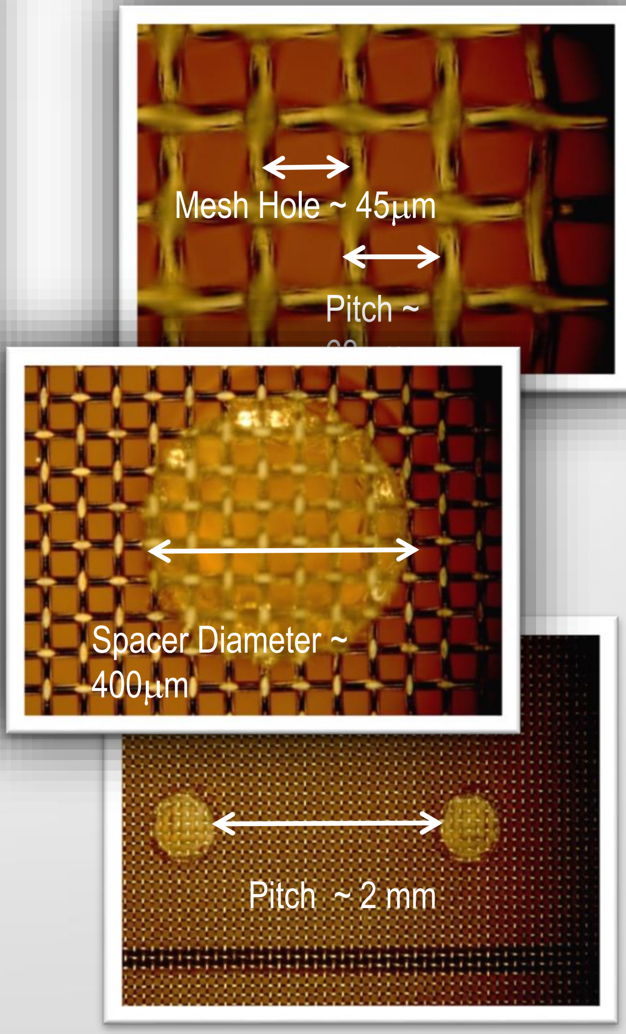


4. Case Studies

- ✓ Gain
- ✓ Transmission
- ✓ Energy resolution, temporal resolution, spatial resolution
- ✓ Ion back-flow
- ✓ Distortion
- ✓ Imperfections

Bulk Micromegas





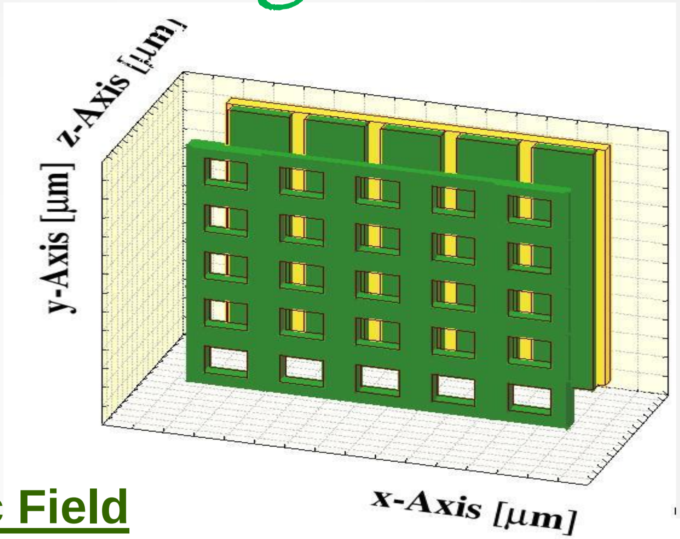
Specifications

- **Active area: 15x15 cm^2**
- **Amplification gap: 64 /128 / 192 / 220 μm**
- **SS wire diameter: 18 μm, pitch 63 / 78 μm**
- **Spacer diameter: 400 μm, pitch 2 mm**

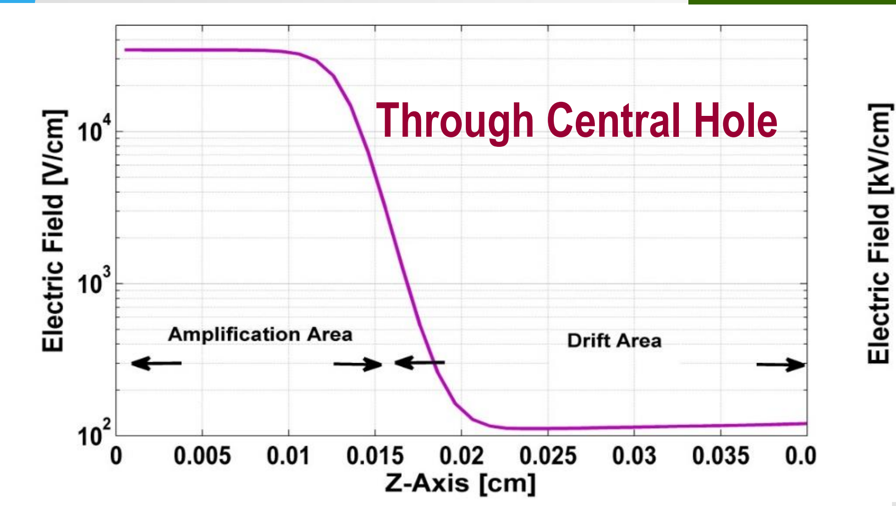
Numerical Bulk Micromegas

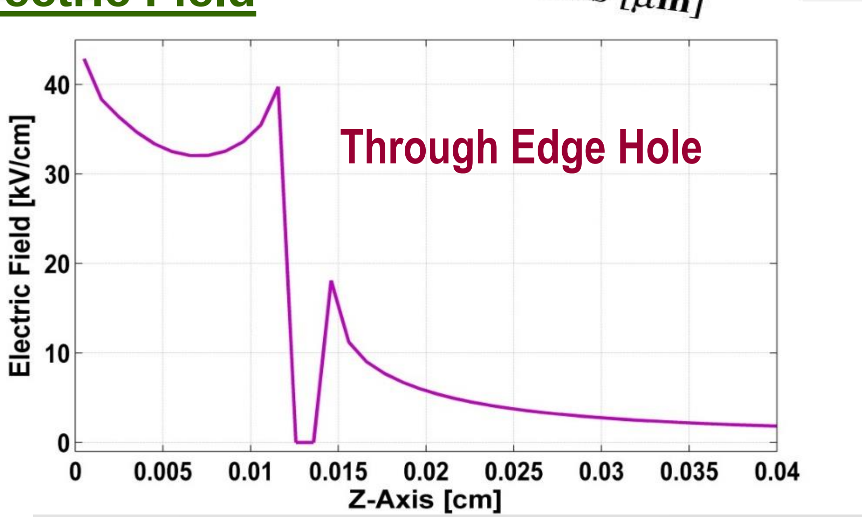
Model using GARFIELD →

- *A drift plane*
- *A micromesh*
- *Anode strips*
- *A dielectric substrate*



Axial Electric Field

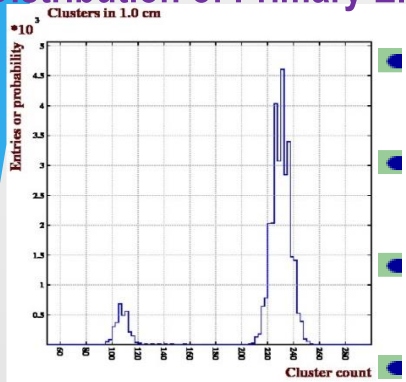




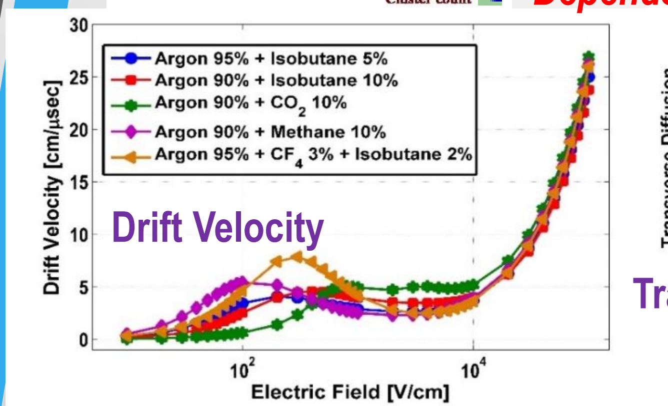
The axial electric field through the central hole is different from any edge side hole

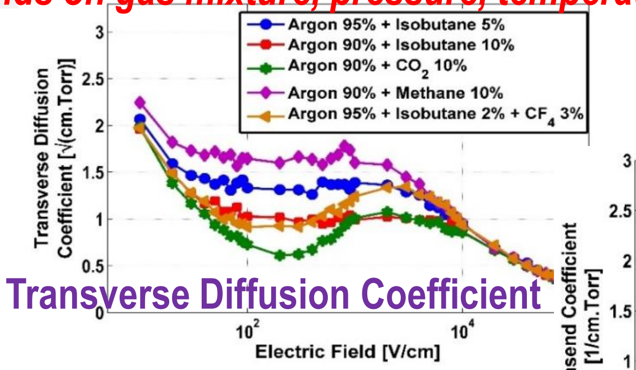
Ionization and Transport in Argon-based Mixtures

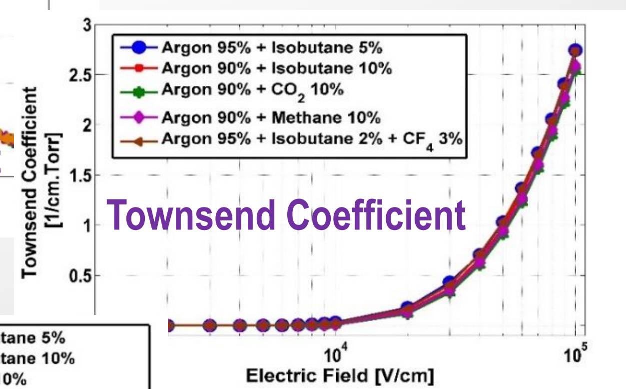
Distribution of Primary Electrons

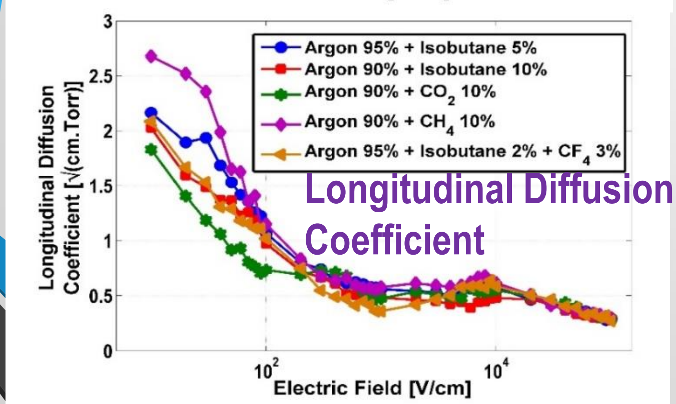


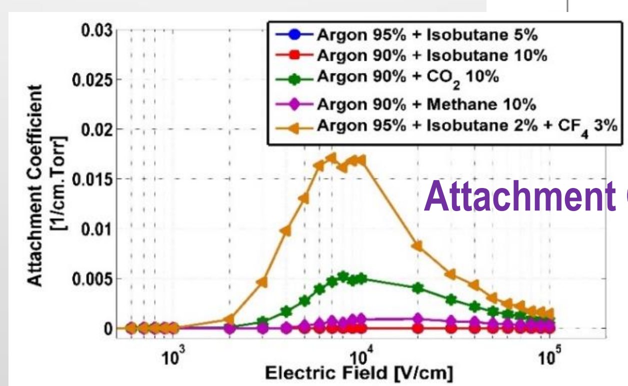
- *Ionization and excitation of gas molecules; Creation of primary electron-ion pair in clusters;*
- *Drift of electrons and ions in the opposite direction due to the electric field; effect of diffusion of electrons drift path*
- *Secondary ionization of electrons at high electric field due to Townsend coefficient; attachment of electrons during drift*
- *Depends on gas mixture, pressure, temperature*



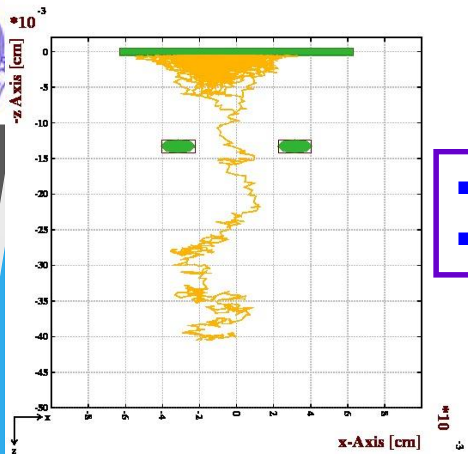




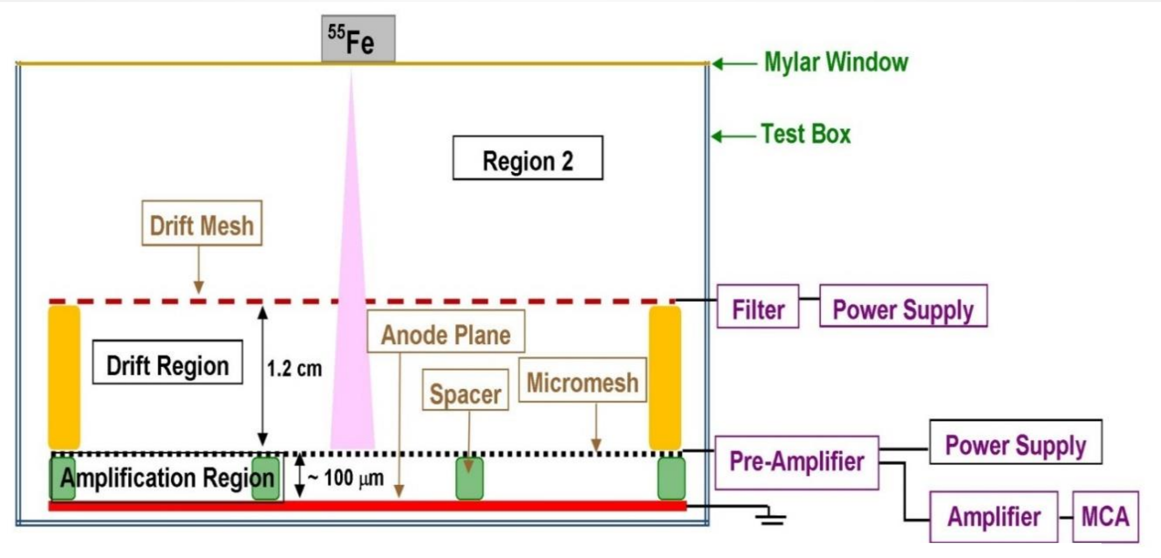




Estimation of Detector Gain



- Gain: final number of electrons / primary electrons
- Depends on detector geometry, voltage setting, gas mixture



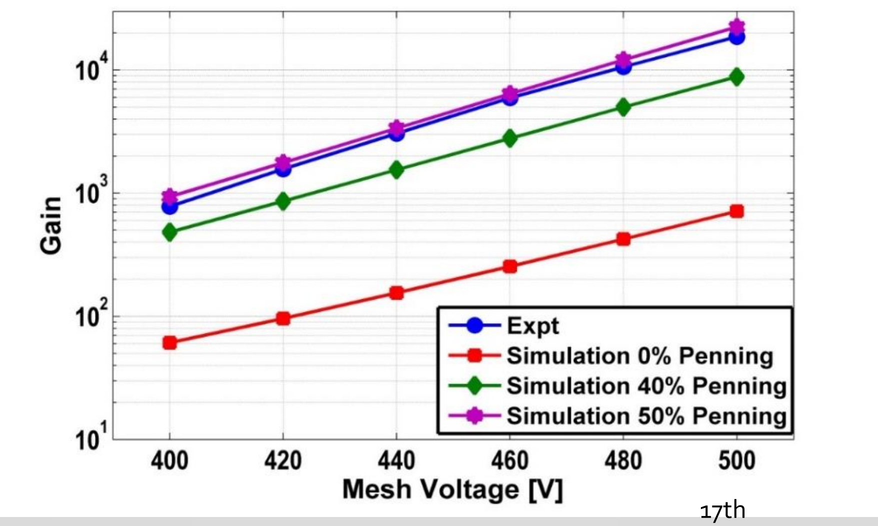
Experiment: kP/N_p,

N_t → Total electrons

N_p → Primary electrons

k → Constant

P → Peak Position



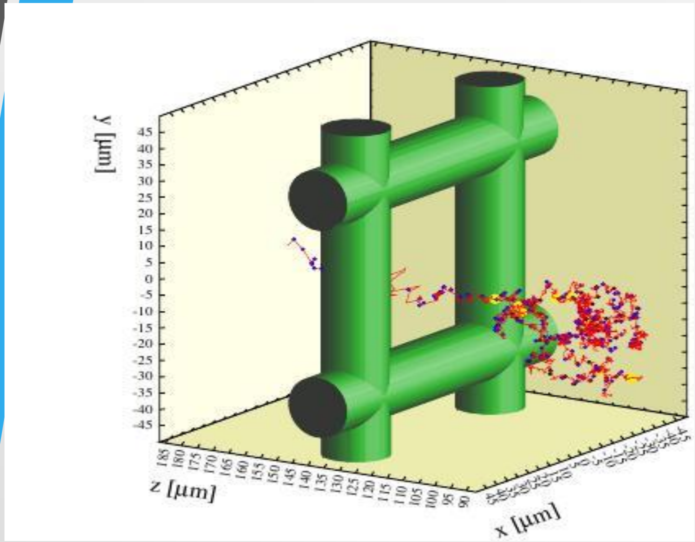
Simulation:

❖ Monte Carlo Method:

1) drifting of initial electron from specified point

2) creation of secondary electrons for each step according to Townsend and attachment coefficient

Estimation of Electron Transmission

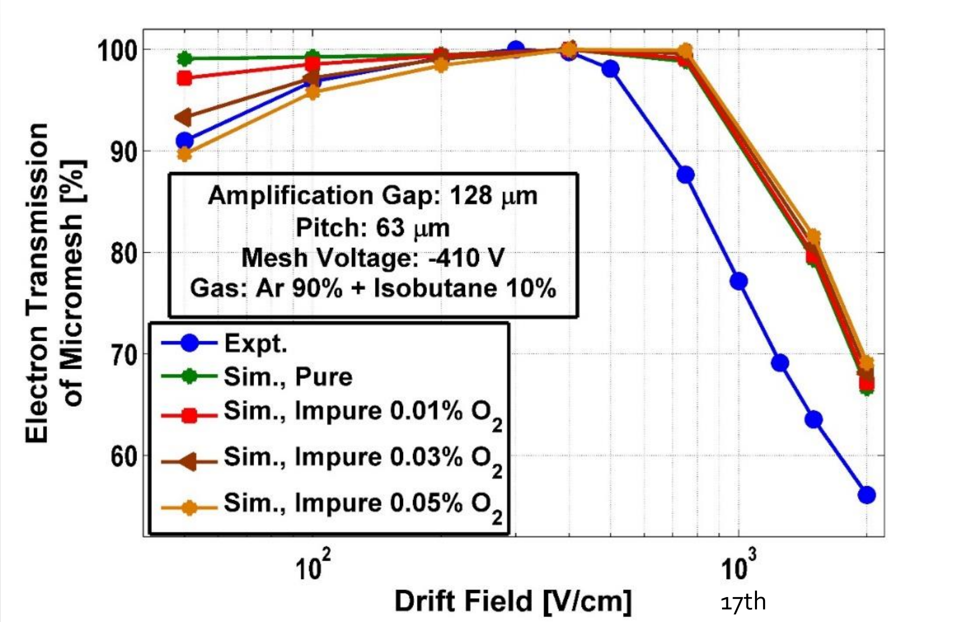


Fraction of electrons arriving in amplification region
- *Depends on field ratio, drift voltage*
- *Depends on hole-pitch, amplification gap*
- *Depends on gas mixture*

Every electron collision is connected with red lines,
• inelastic collisions • excitations • ionizations.

Experiment :
Ratio of signal amplitude at a given E_{drift} over signal amplitude at E_{drift} where gain is maximum

Simulation:
Microscopic tracking of electrons from randomly distributed points



Excellent work has also been carried out by Fabian Kuger using Garfield++

Energy Resolution: How precisely the energy of radiation can be measured?

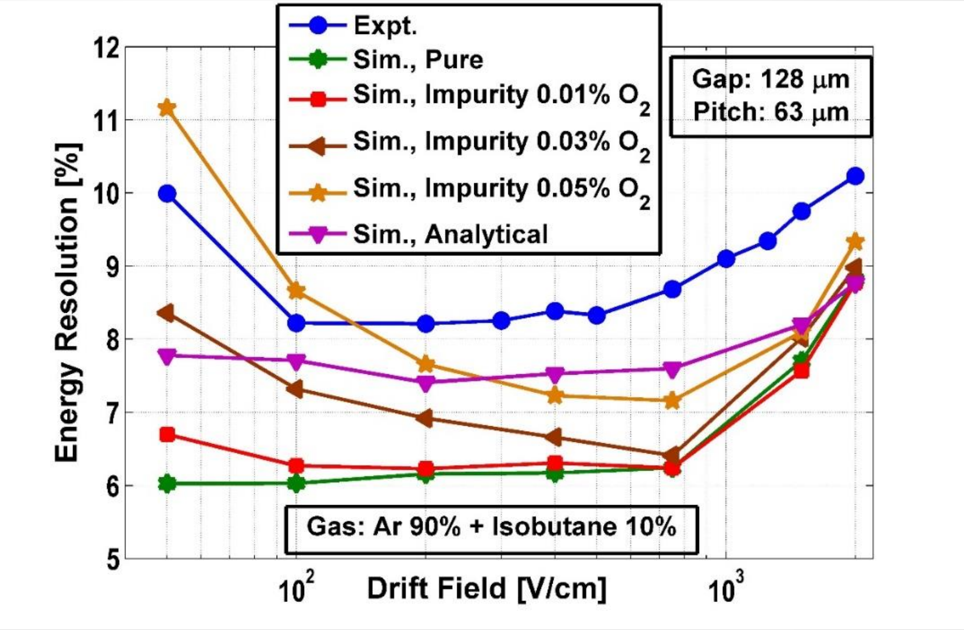
- Depends on statistical fluctuation of primary number of electron-ion pairs, gain variation, transmission
- Inhomogeneity of gas composition, pressure and temperature fluctuation, electronic noise also affect the resolution

Experiment : $R = \sigma_P/P$, where
$\sigma_p \rightarrow$ r.m.s. of the pulse height distribution
$P \rightarrow$ peak position

Simulation:

$$R = \frac{\sigma_E}{E} = \sqrt{\frac{F}{n} + \frac{1}{n}\left(\frac{\sigma_G}{G}\right)^2 + \frac{(1-\eta)}{\eta n}}$$

R: Resolution; n: Primary Electrons; F: Fano Factor; η: Electron Transmission; G: Gain; σ_G : Gain Variation



Temporal Resolution

Depends on: 1) Primary Statistics, 2) Diffusion, 3) Gain fluctuation, 4) Measurement threshold

Our calculation:

- Consider cosmic Muon (energy 1 – 3 GeV) track
- For a particular track, recorded the drift time of electron which induces detectable signal

Assumption:

- Equal contribution of all the track, inclined at different angle
- Threshold is simply a fraction of the signal peak

Ignored:

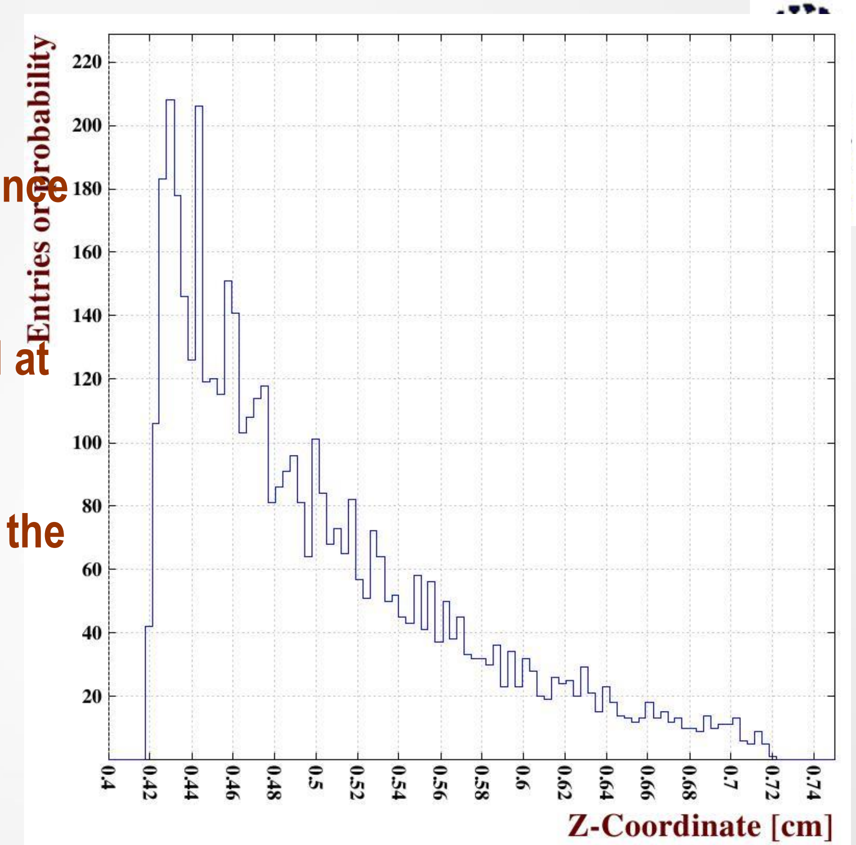
- Effects of electronics such as shaping

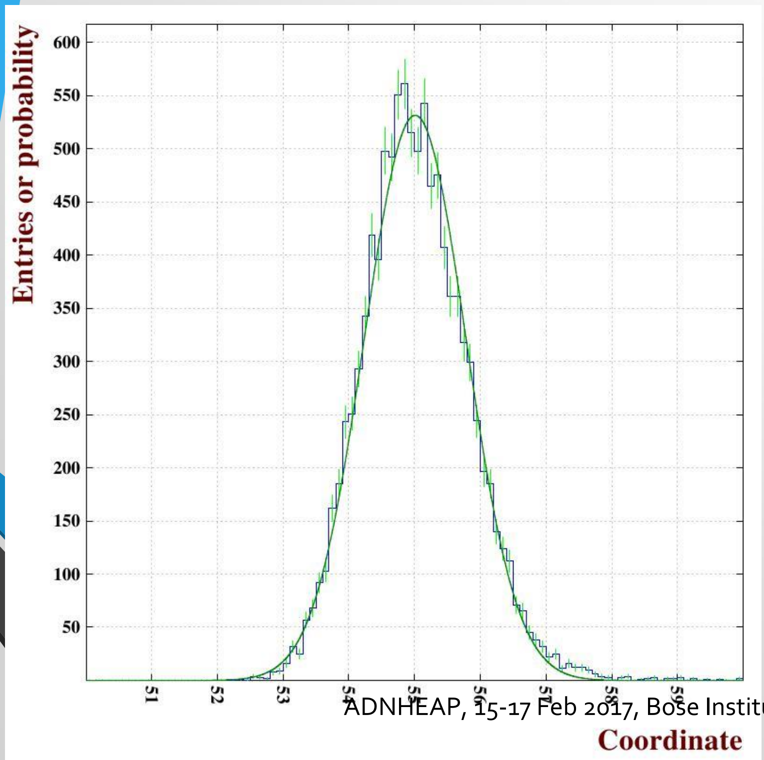
Primary Statistics:

✓ Number of primary ionization along a given distance follows Poisson Statistics

✓ From event to event the electron is not produced at same position

✓ The distance of electron from top which reaches the readout first, is distributed with decreasing exponential





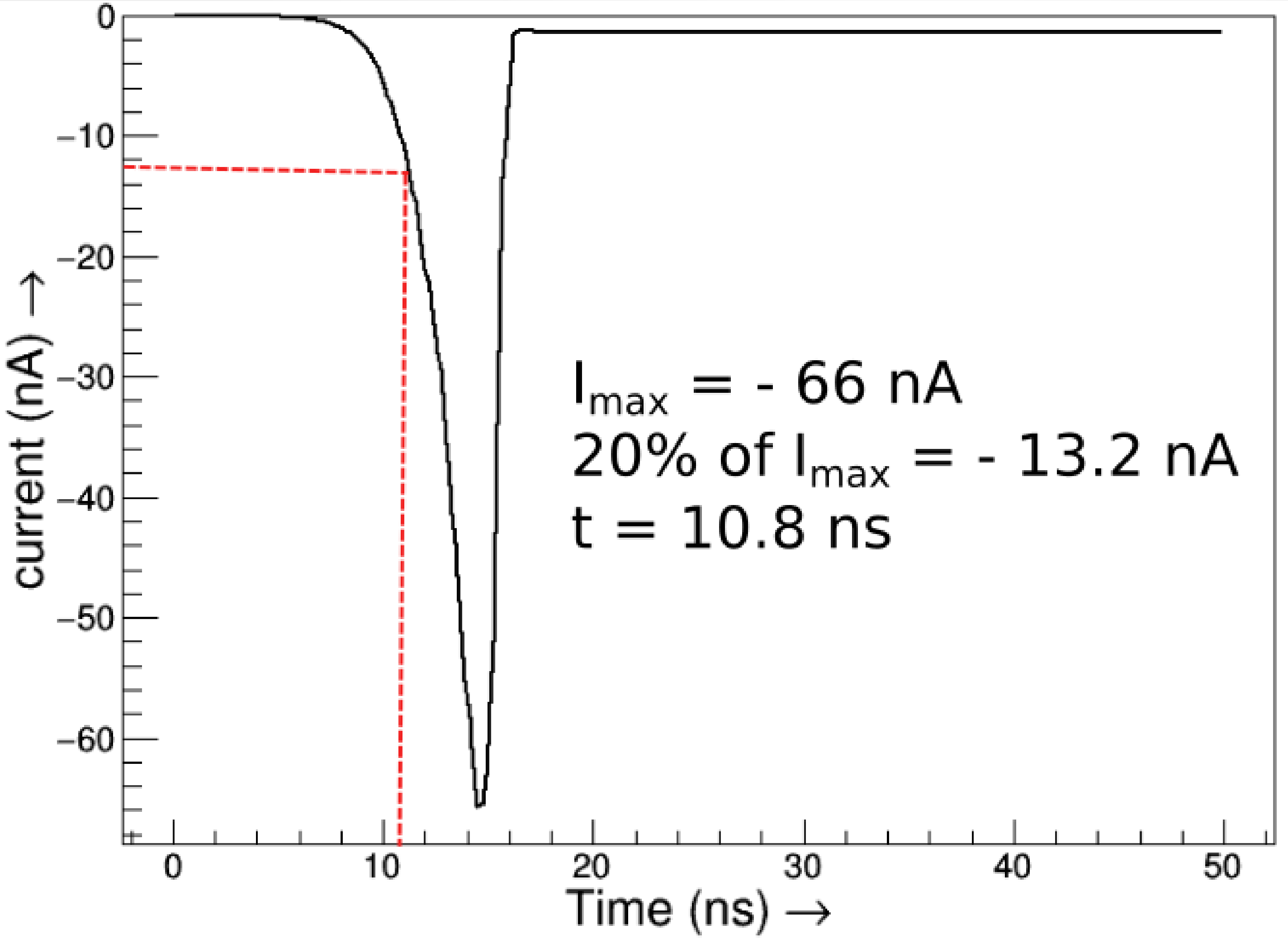
Diffusion:

➢ Electrons starting from same position arrive at different times

➢ Gaussian distribution

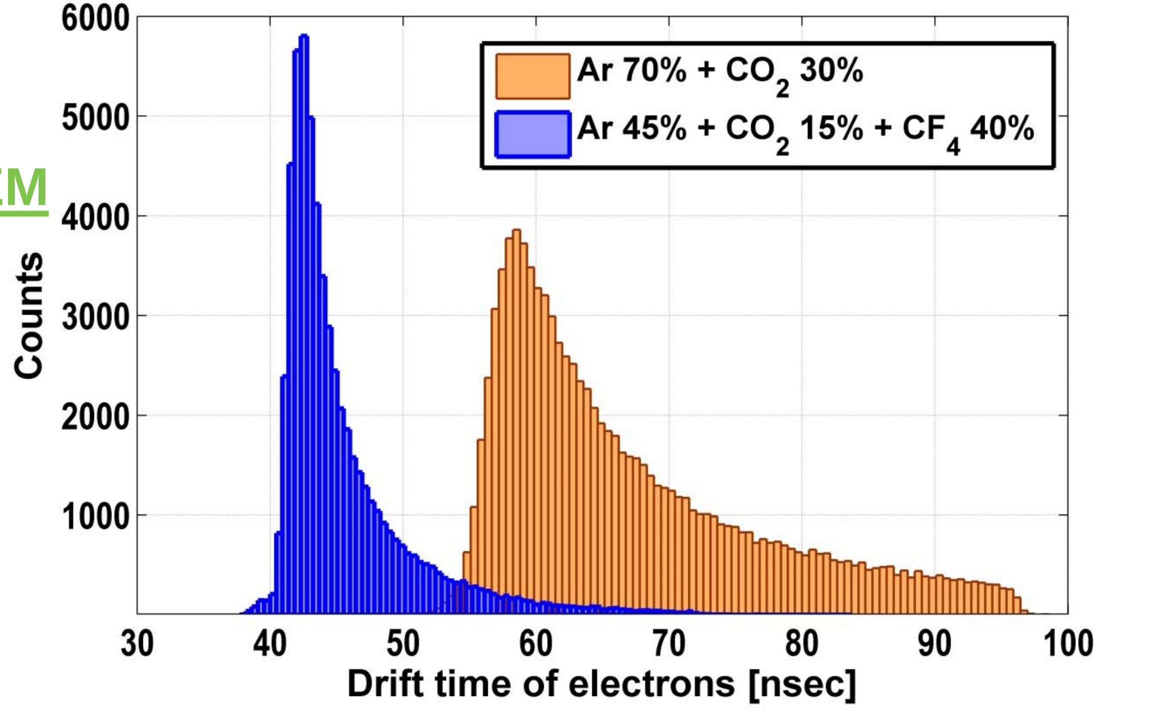
➢ With varying distance, the mean and the sigma change accordingly

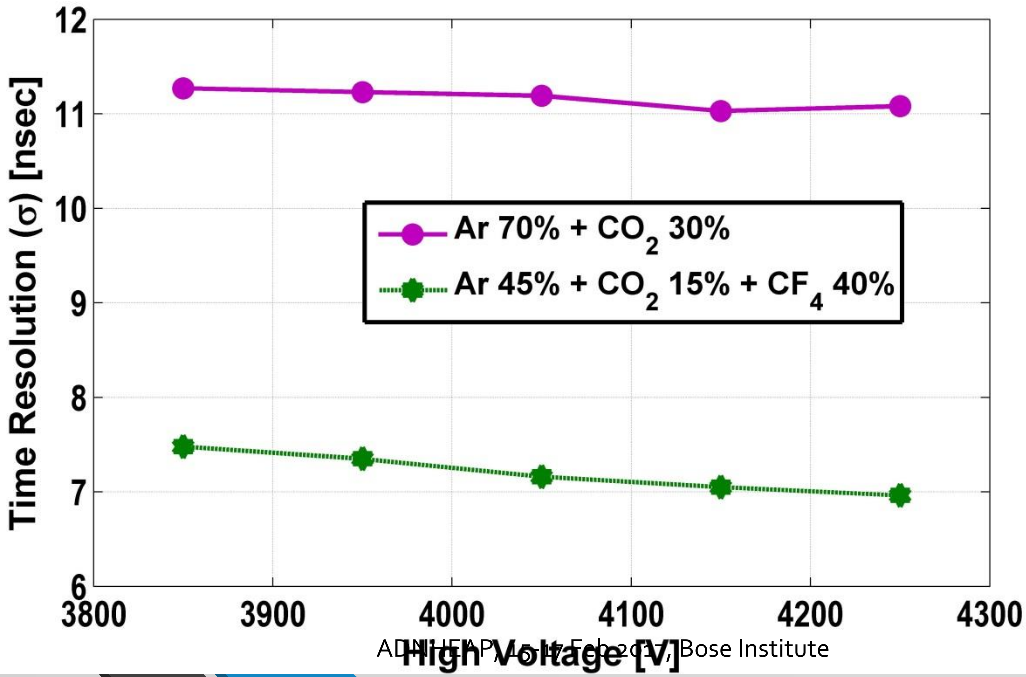
Effect of gain fluctuation and threshold



I_{max} = - 66 nA
20% of I_{max} = - 13.2 nA
t = 10.8 ns

Time Spectrum of Triple GEM

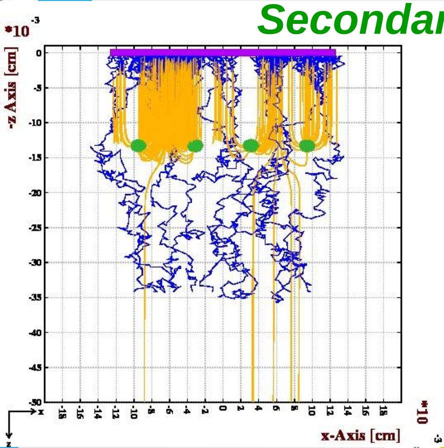


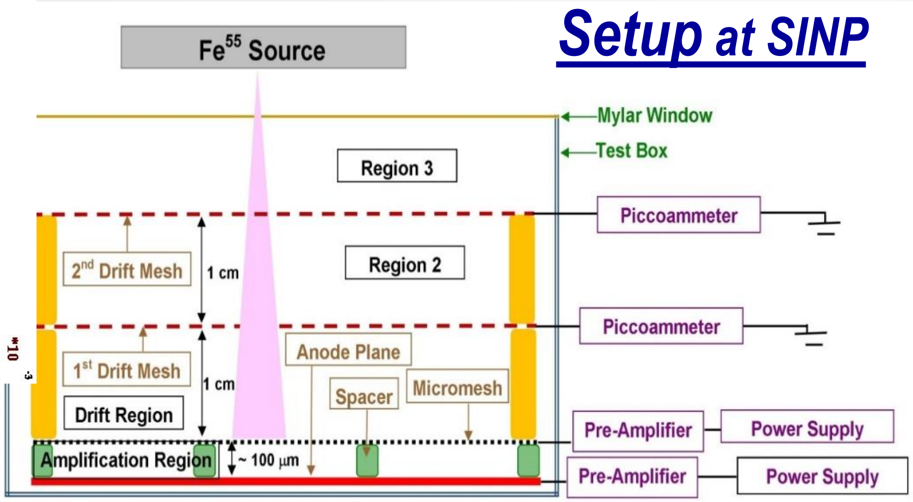


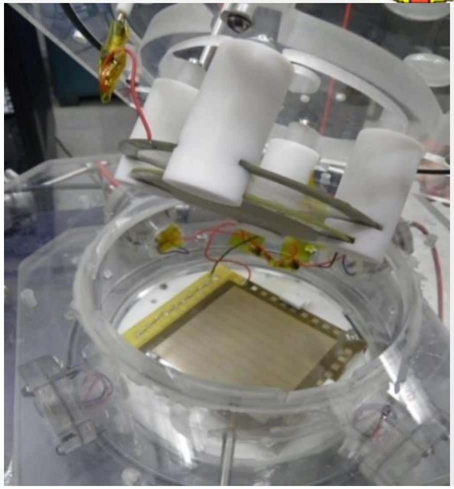
Variation of Temporal Resolution with Applied HV in Argon-based Gas Mixture

Ion Backflow

Secondary ions from amplification region drift to drift region





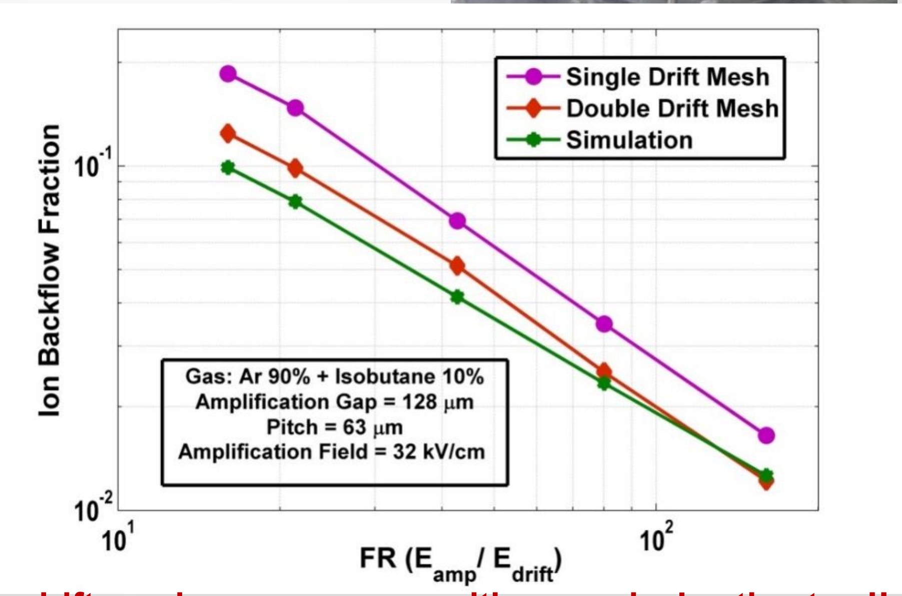


Backflow fraction: N_b/N_t

$N_b \rightarrow$ *backflowing ions*

$N_t \rightarrow$ *total ions*

- Implementation of 2nd drift mesh
- Currents are measured using Pico ammeter **(CAEN AH401D, Danfysik Current Integrator 554)**
- Electrode from which current is measured, is grounded, Potential of other electrodes are adjusted to maintain the correct field configuration



Experiment: $\frac{N_b}{N_t} = \frac{I_C}{(I_M + I_C)}$

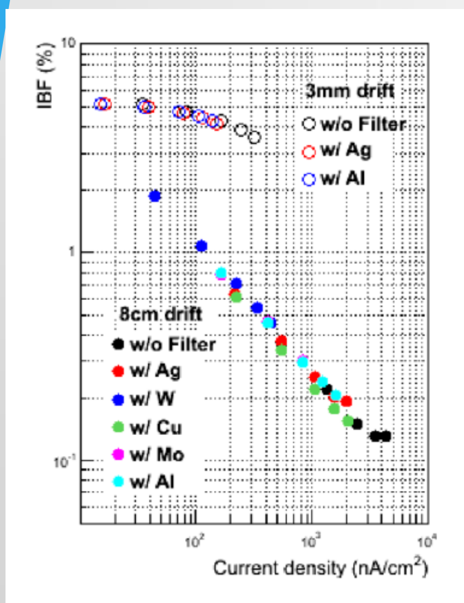
Simulation: $\frac{N_b}{N_t}$

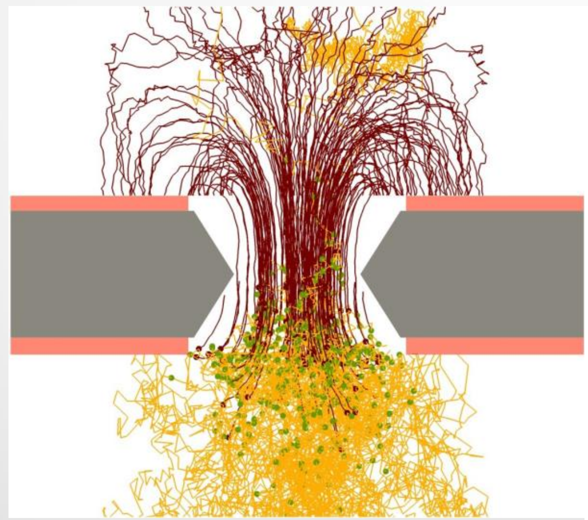
Experimental estimates using two drift meshes agree more with numerical estimates !!

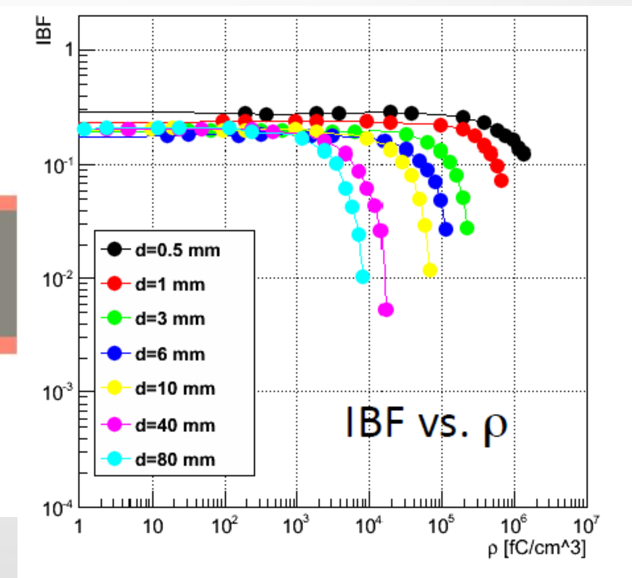
GEM-TPC Ion Back Flow

Applications:

- TPC GEM: ion backflow
- GEM: multiplication process and polyimide properties; charging up
- MicroMegas: timing and effects of resistive layers

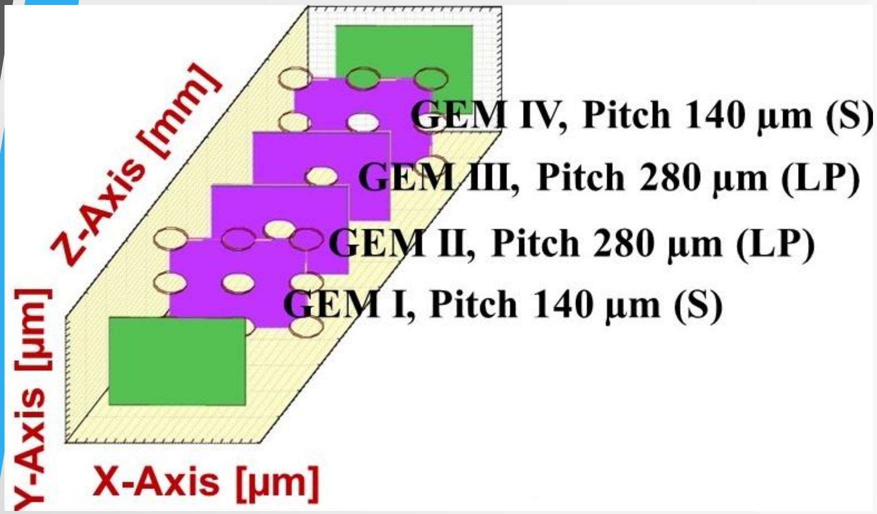






ALICE TPC end-cap upgrade studies of rate dependence of the Ion Back Flow in GEM.
Left: measurement; Right: Garfield++ simulation results

ALICE



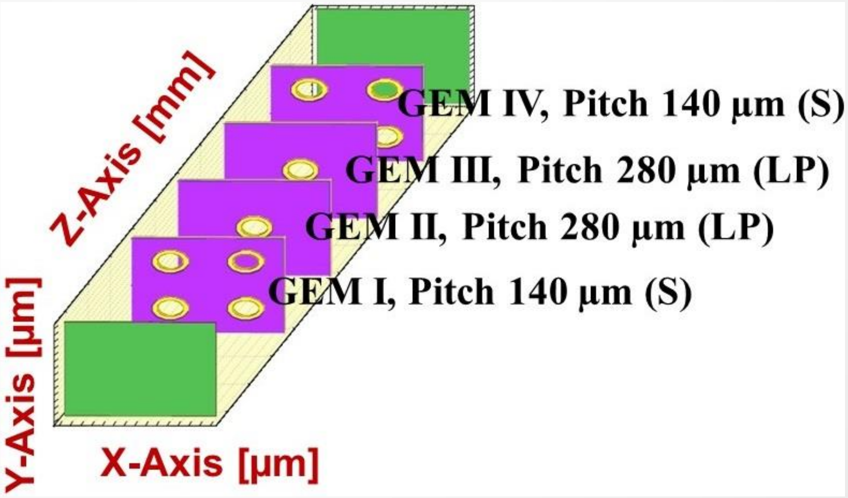


Table 1: Design parameters of GEM-based detectors.

Polymer substrate	50 μm
Copper coating thickness	5 μm
Hole diameter (copper layer)	70 μm
Hole diameter (Polymer substrate)	50 μm
Hole to hole pitch	140 / 280 μm
Drift Gap	3 mm
1st Transfer gap	2 mm
2nd Transfer gap	2 mm
3rd Transfer gap	2 mm
Induction gap	2 mm

Table 2: Field configuration of quadruple GEM detector.

Drift Field	400 V/cm
E_{GEMI}	40 kV/cm
Transfer Field I	4000 V/cm
E_{GEMII}	35 kV/cm
Transfer Field II	2000 V/cm
E_{GEMIII}	37 kV/cm
Transfer Field III	100 V/cm
E_{GEMIV}	45 kV/cm
Induction Field	4000 V/cm

ALICE

Table 3: ε_{coll}, ε_{ext} and ε_{tot} of quadruple GEM detectors.

Geometry	B [T]	ε_{collI} [%]	ε_{extI} [%]	ε_{collII} [%]	ε_{extII} [%]	$\varepsilon_{collIII}$ [%]	ε_{extIII} [%]	ε_{collIV} [%]	ε_{extIV} [%]	ε_{tot} [%]
QGemI	0	99.30	39.56	6.73	35.43	15.1	16.02	91.53	43.98	0.0091
QGemI	0.5	99.59	40.02	6.47	36.16	14.76	16.08	90.97	45.49	0.0092
QGemII	0.5	89.57	43.09	7.14	34.59	12.97	14.26	97.14	46.10	0.0079

Table 4: Ion collection efficiency of quadruple GEM detectors.

Geometry	B [T]	GEMI [%]	GEMII [%]	GEMIII [%]	GEMIV [%]	Drift [%]
QGemI	0	2.5	0.4	1.3	93.2	2.7
QGemII	0.5	2.3	0.4	1.3	93.0	2.8
QGemII	0.5	5.9	0.5	1.2	92.3	0.1

Low transmission, moderately high ion back-flow.

Scope of improvement?

A Triple GEM configuration for ALICE

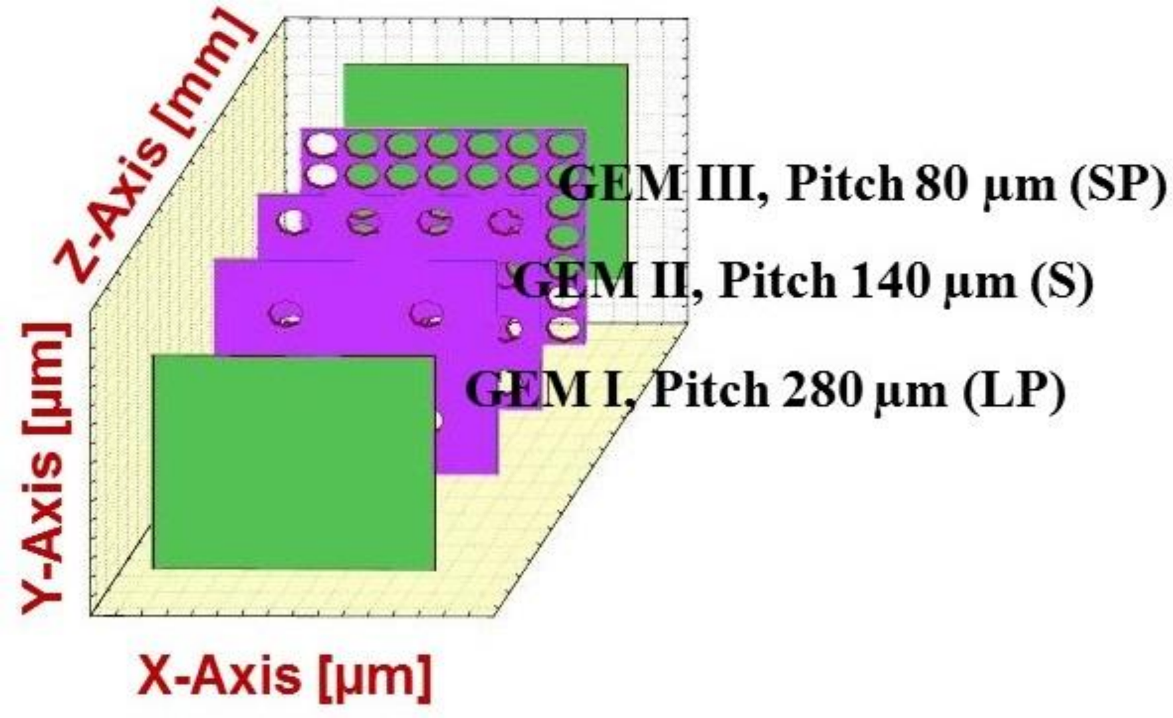


Table 6: ε_{coll}, ε_{ext} and ε_{tot} of triple GEM detector.

ε_{collI} [%]	ε_{extI} [%]	ε_{collII} [%]	ε_{extII} [%]	$\varepsilon_{collIII}$ [%]	ε_{extIII} [%]	ε_{tot} [%]
20.0	29.0	64.0	38.0	89.0	24.0	0.3

Table 5: Field configuration of triple GEM detector.

Drift Field	400 V/cm
E_{GEMI}	52 kV/cm
Transfer Field I	1750 V/cm
E_{GEMII}	40 kV/cm
Transfer Field II	3600 V/cm
E_{GEMIII}	35 kV/cm
Induction Field	4000 V/cm

Table 7: Ion collection efficiency of triple GEM detector.

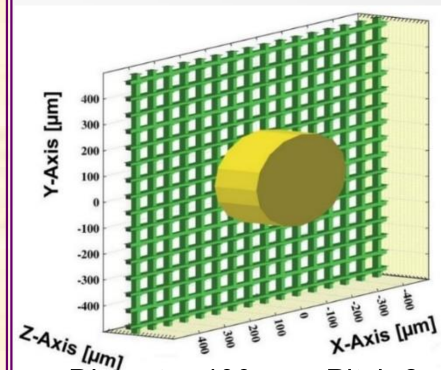
GEMI [%]	GEMII [%]	GEMIII [%]	Drift [%]
8.9	12.8	77.4	0.2

- Improvement observed in electron transmission
- This configuration is also under study and being optimized

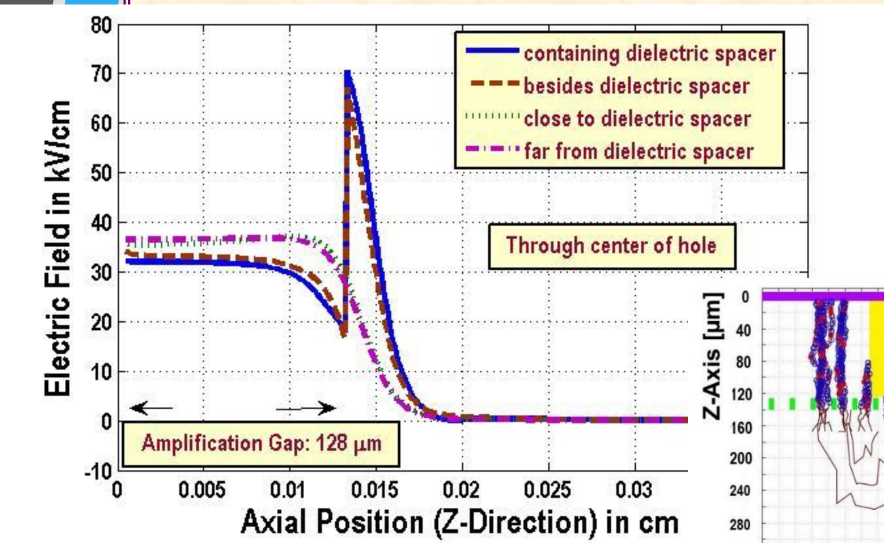
Purba Bhattacharya and Hugo Natal da Luz, Instituto de Fisica, Universidade de Sao Paulo, Brazil

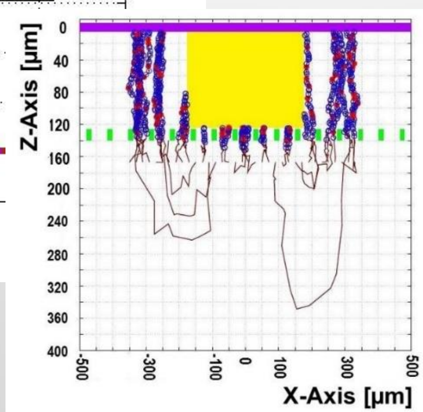
Position resolution: Effect of Spacers

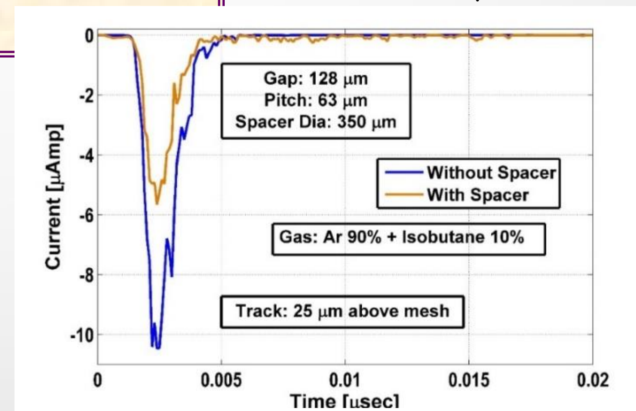
- ✓ Spacers cause significant perturbation resulting in increased field values, particularly in the regions where cylinders touch the mesh
- ✓ Electron drift lines get distorted near the spacer, some electrons are lost on it, resulting in a reduced gain
- ✓ Due to the reduced gain, electron signal strength gets affected significantly, the signal profile consists of a long tail resulting from the distorted drift
- ✓ Due to the dead regions introduced by the spacer, the readout pads below or close to the spacers are found to be affected which leads to inefficiencies in track reconstruction

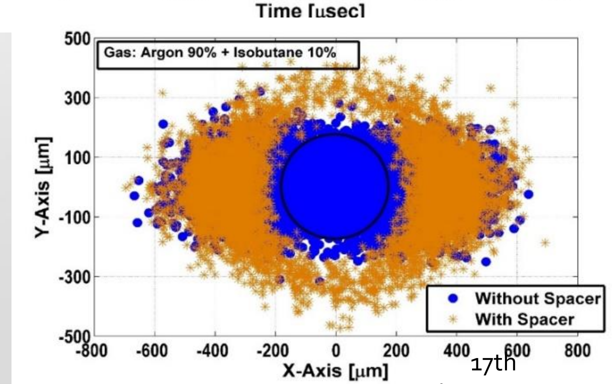


Diameter 400 μm, Pitch 2 mm

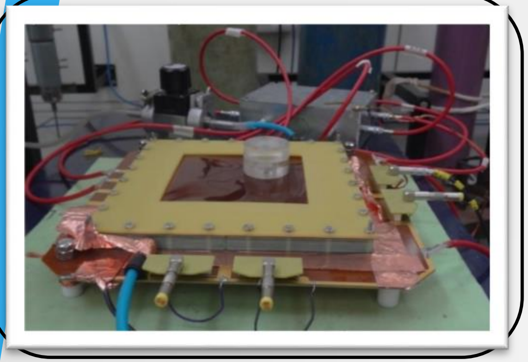


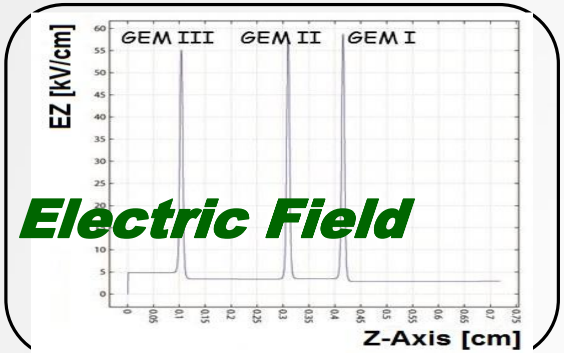


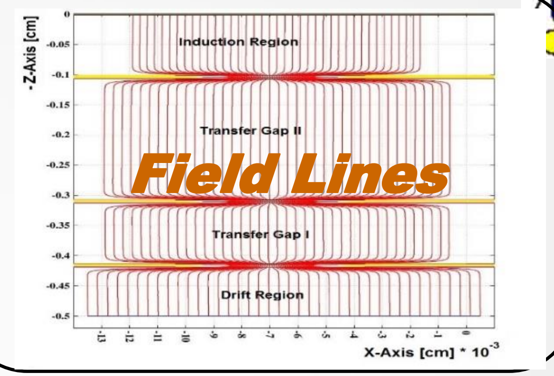


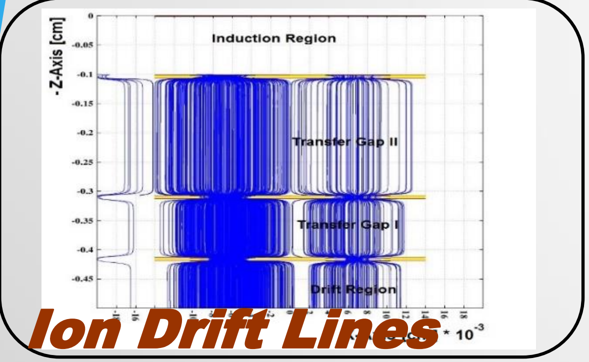


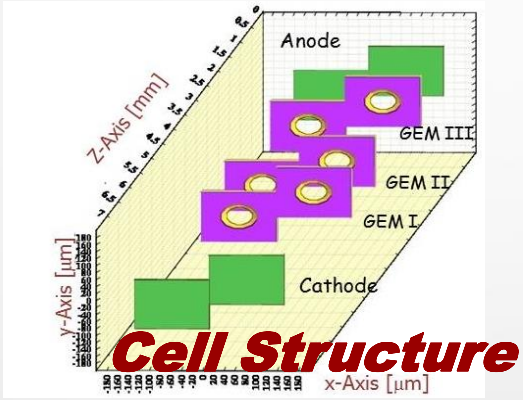
Triple GEM @ CMS

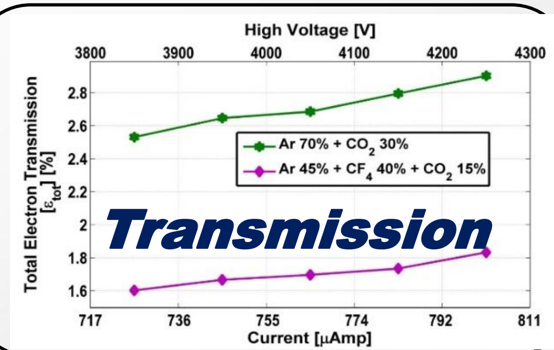


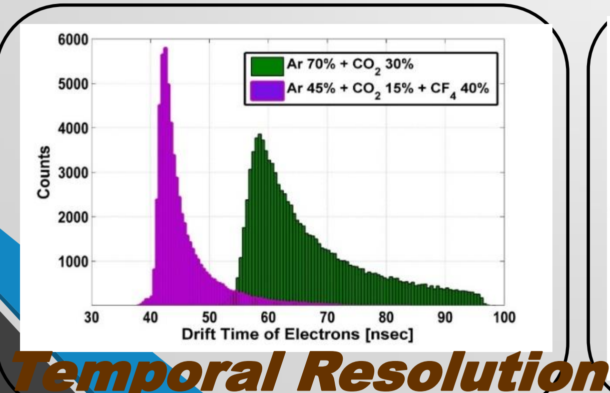


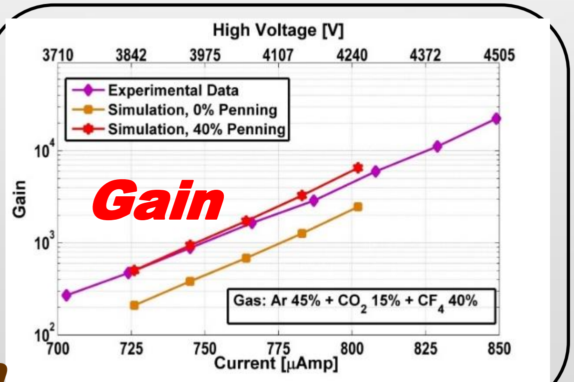


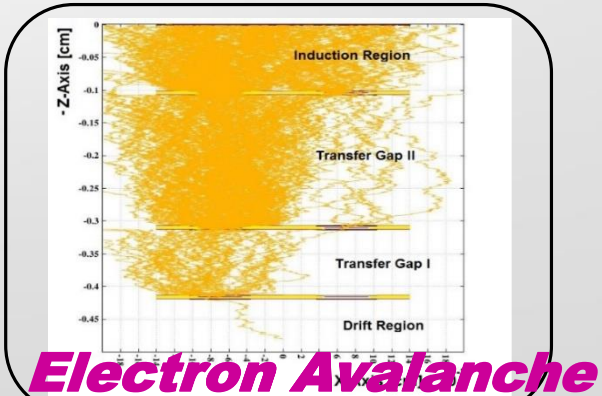




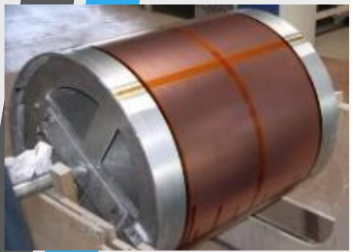








ILC



Large Prototype TPC

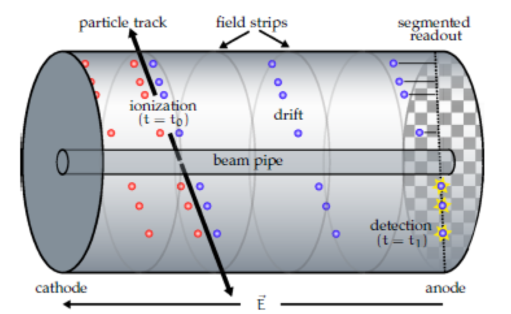
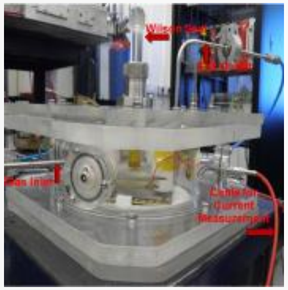
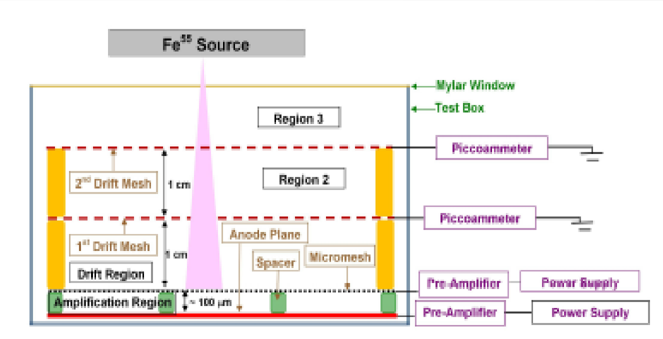
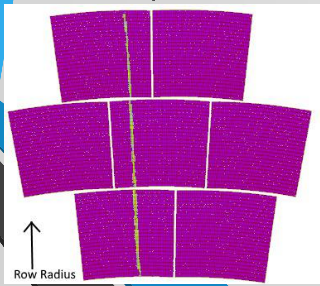


Figure 1.1: Operation principle of a TPC. An additional magnetic field in parallel with the electric field enhances the spatial resolution and enables measurements of particle momenta.



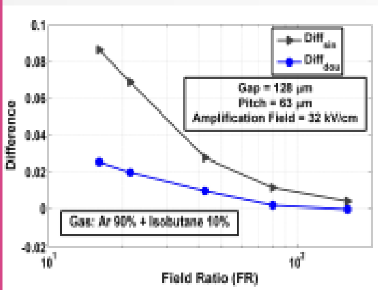


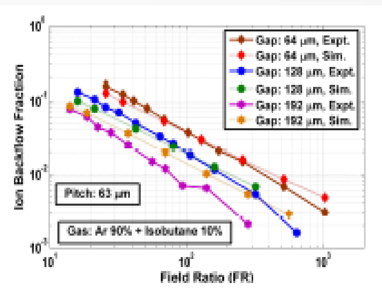
Endplate

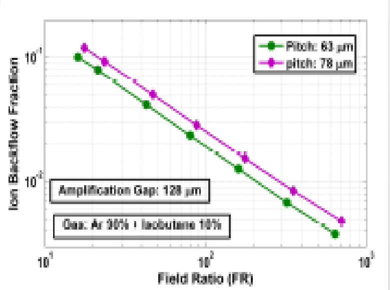


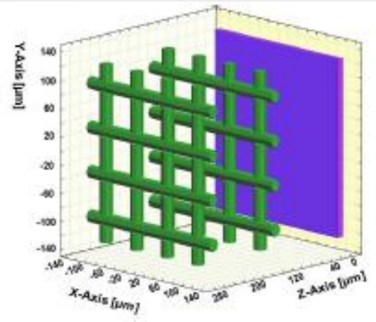
Micromegas readout

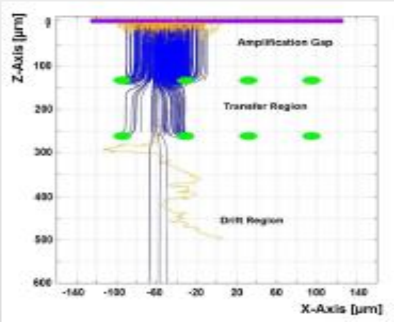
- IBF found to be minimum at low drift fields and high amplification fields.
- Less IBF with larger gap and smaller pitch .
- Use of a double micro-mesh reduces IBF by a factor of 2 w.r.t single micro-mesh although it affects electron transmission , gain and energy resolution.

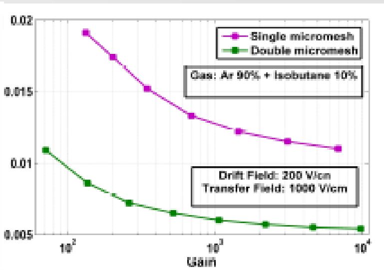




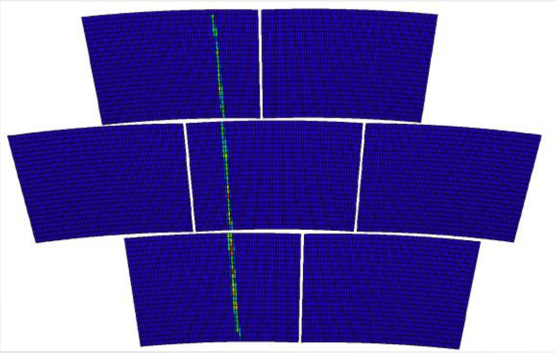




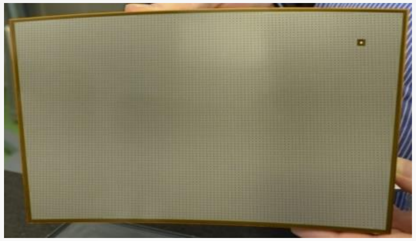




Distortion in Micromegas based TPC @ILC

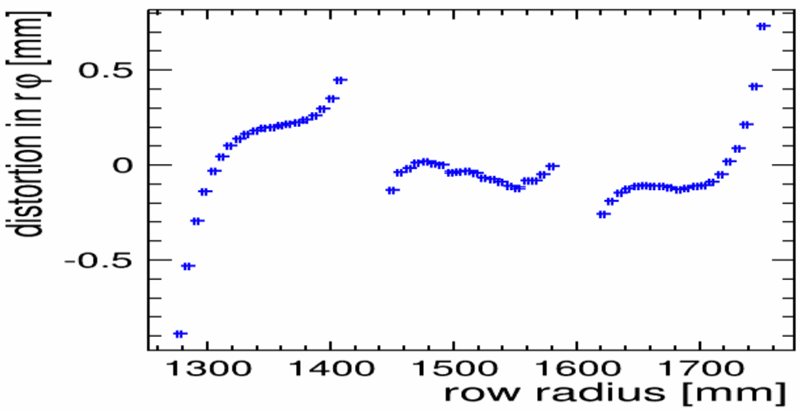


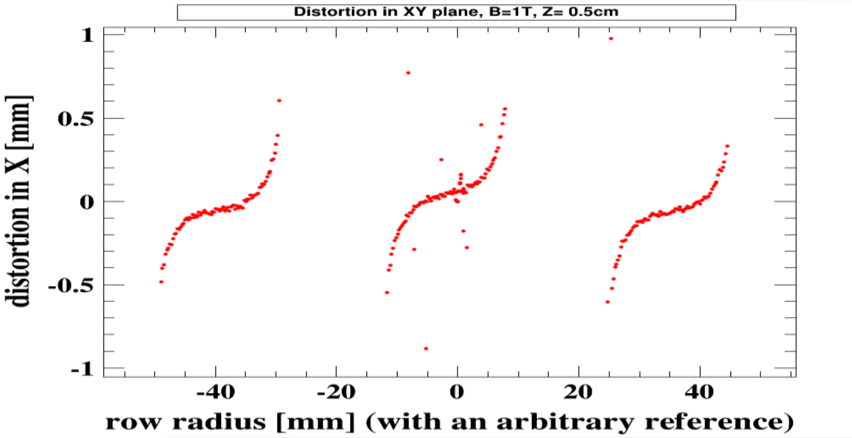
All modules are identical keystone shaped.
Gap between the modules = 3 mm



A resistive MM module for the LPTPC

- Module size: 22 cm × 17 cm
- Readout: 1726 pads, 24 rows
- Pad size: ~3 mm × 7 mm



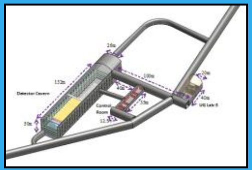


Distortion as observed in ***Experiment***
At B=1T. Track is a 5 GeV electron beam.
Correction for the misalignment of the modules is not done here.

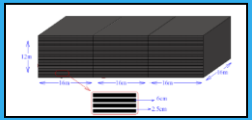
Distortion as obtained from ***Simulation***
at B=1T. The track consists of of 457 equidistant primary electrons.
Result is averaged over 50 tracks.

INO-ICAL: Study on RPCs

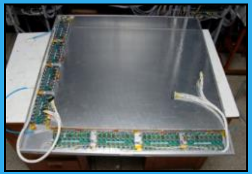
Pottipuram



Underground Facility



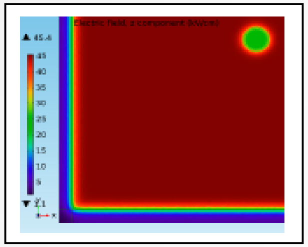
Iron Calorimeter (ICAL)



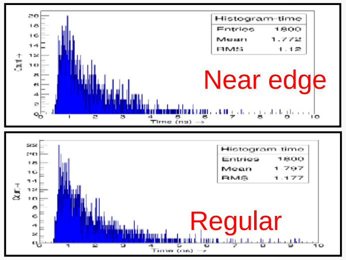
RPC Module

Geometry effect

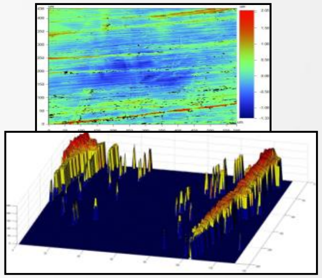
Simulated the effect of edge, spacer on electric field, time response. Effect of surface asperity simulation underway.



Electric field map



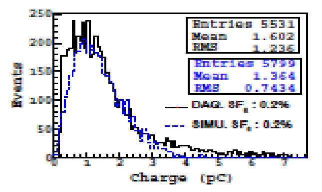
Time response

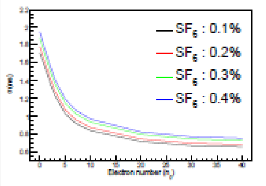


Surface asperity

Gas mixture effect

Effect of different concentrations of SF6 (used to control streamer) measured and simulated.

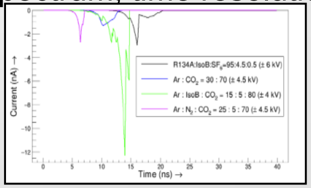




Effect of SF6 on charge spectrum, time resolution

Eco-friendly gas mixture

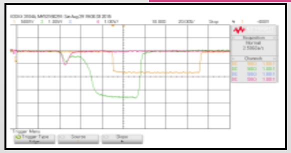
Simulation with several gas mixture is underway to explore eco-friendly mixtures.



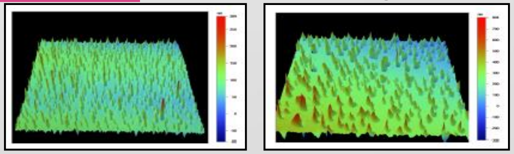
Current signal

Ageing studies

Effect of injected humidity on response and electrodes measured. Simulation to begin shortly.

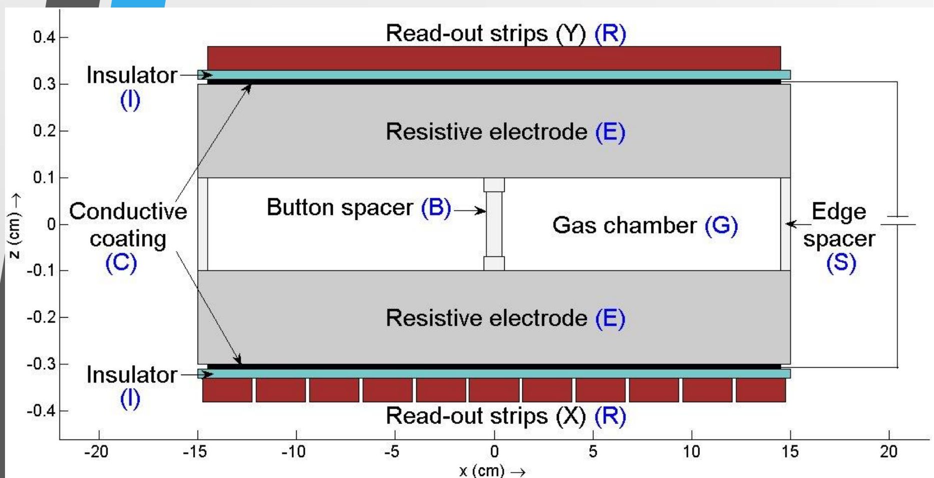


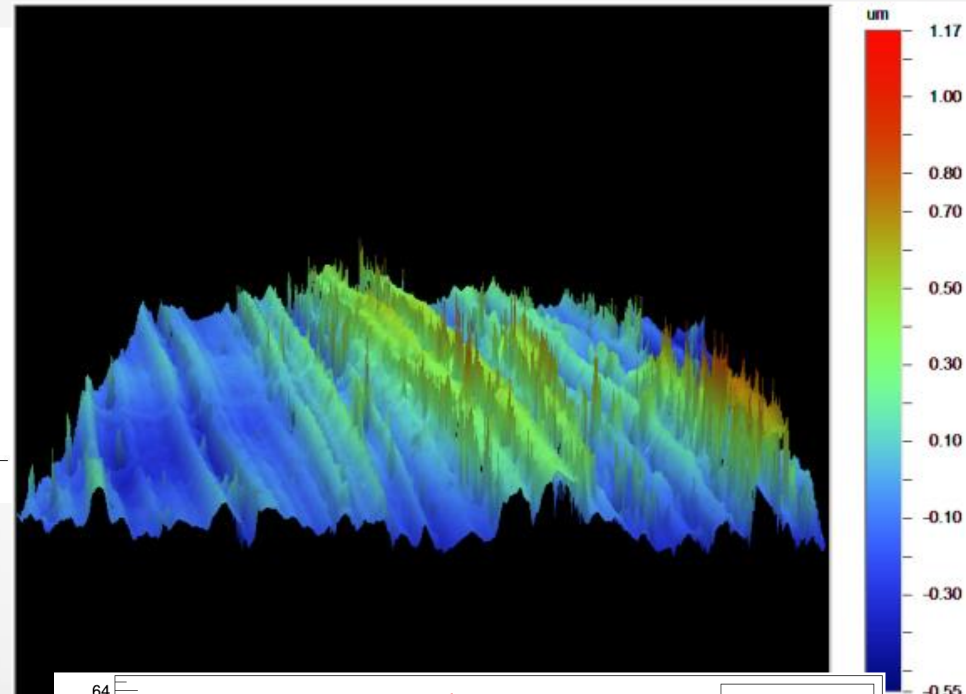
Signal with dry and wet gas

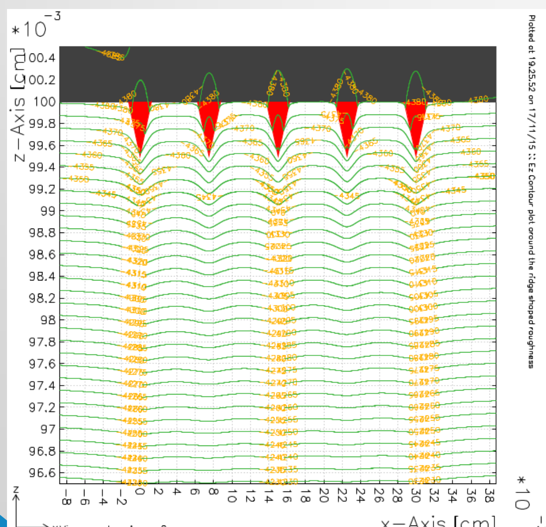


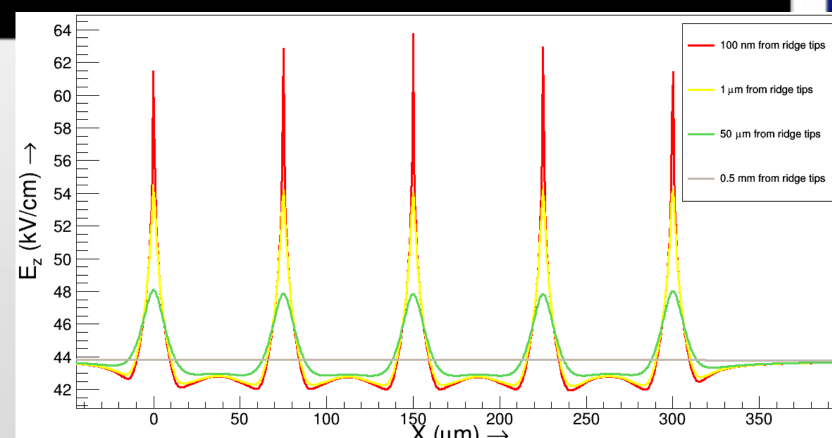
Glass electrodes after wet gas flow

Roughness in Resistive Plate Chambers @INO



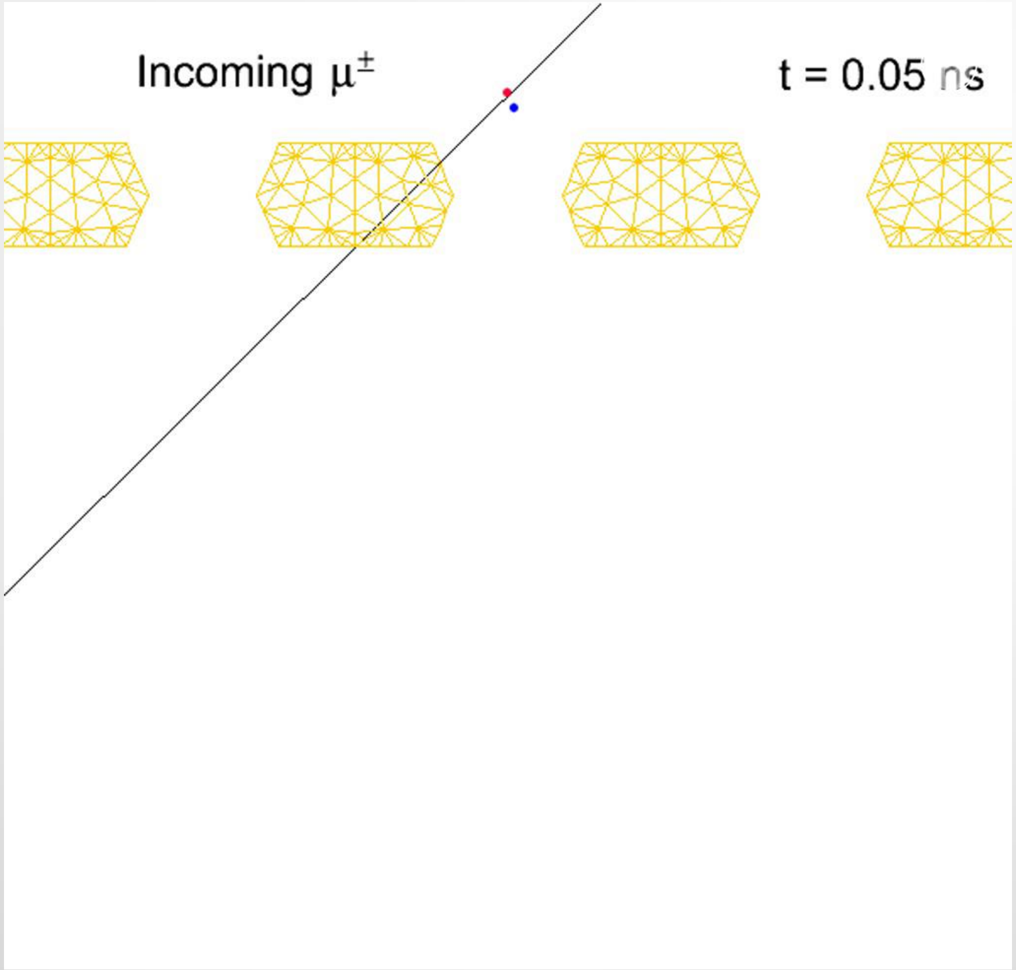






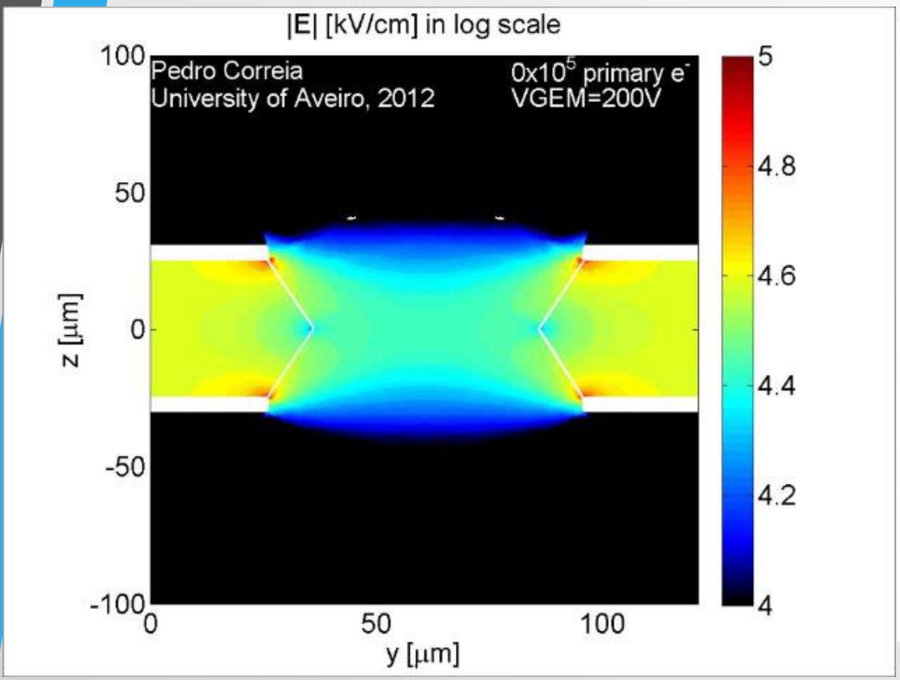
MPGD Simulation Tools

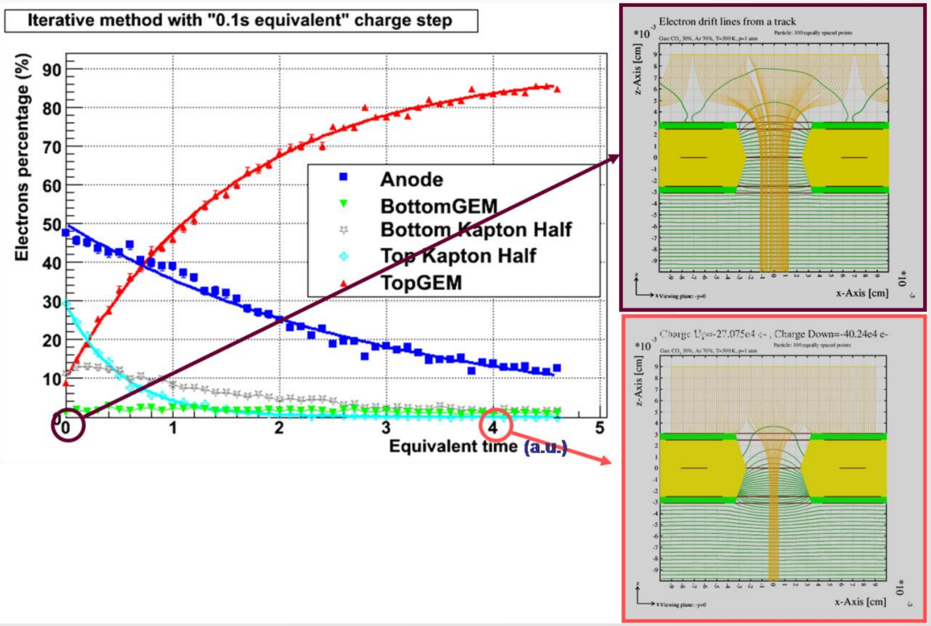
GEM Avalanche Development



MPGD Simulation Tools

GEM Charging Up





Problems looking for Solutions

Some attempts have been made already

- Volume currents
  - current through solid-state, dielectric materials, simulation of the VI curve
- Space charge
  - distortion of field; reduction of ionization probability
- Discharges
  - causing permanent damage to detectors, electronics
- Resistive layers
  - spark protection, improved spatial resolution
- Ageing
  - insulating deposit on anodes and cathodes; formation of strong dipoles, field emissions and micro-discharges – Malter effect

Description Far from Complete

- Gravitation, Thermodynamics, Optics
- Fluid mechanics (micro / compressible / Stokes)
- Electro-hydro dynamics (laminar / turbulent)
- Structural issues
- Solid state physics
- Wetting, Self-cleaning
- Eminently multi-physics (and chemistry) problem involving multiple temporal and spatial scales
- Could easily pass as one of the Grand Challenge Computing Problems!

Summary

Device Physics of Gaseous Ionization Detectors:

- Detector dynamics through complementary numerical and experimental analysis: gain, transparency, energy, temporal and spatial resolutions
- Optimization of geometrical, electromagnetic designs and environment friendly gas mixtures
- Development of detailed understanding of physics issues like charging up, ion backflow through numerical and experimental studies.
- Studies on design modifications related to various resistive materials.

Applications:

- Synchronization of device physics studies to the goals of various experiments
- Application of for radiation imaging, including Muon Tomography

Algorithms

- Garfield++
- neBEM geometry modeler (borrow from Geant4)
- Charge diffusion through resistive layers
- Dynamics of charging up of dielectrics
- Effects due to space charge build-up
- Efficient and accurate tomography for radiation imaging applications
- Extremely fast computation (parallel, multi-threaded, multi-core, CPU-GPU, whatever the technology be)
- Improved algorithms (adaptive meshing, FMM, CORDIC)

Outlook

- Calculations for gas detectors are steadily becoming more detailed. However, much effort is necessary to improve understanding and interpretation.
- Despite the limitations, the tools are mature enough for design purposes. Discoveries using these tools seems to be distant, though (hope I am wrong!).
- Improvements in physics modelling and computational techniques are necessary.
- Multi-Physics issues can make the work more complex, but rewarding.
- Exciting times ahead!

Materials Collected From

- Atsuhiko Ochi
- Blum, Rolandi, Riegler
- Heinrich Schindler
- Igor Smirnov
- Paulo Fonte
- Rob Veenhof
- Steve Biagi
- Werner Riegler
- Yukihiro Kato
- Lohse and Witzeing
- Gabriel Croci
- Matteo Alfonsi
- Many others …

Thank you
for your kind attention!