RPCs*: R&D in new applications

P.Fonte for the LIP RPC/RPC-PET team

This talk covers the projects:
RD51 (CERN-based detector research collaboration)
NEULAND (fast neutron detector) - with D. Galaviz, J.Machado, P.Teubig, CFNUL

and it is partially relevant to:
AUGER & cosmic rays
human RPC-PET (+ lab.fis. IST)

* Resistente Produto Caseiro

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Outlook

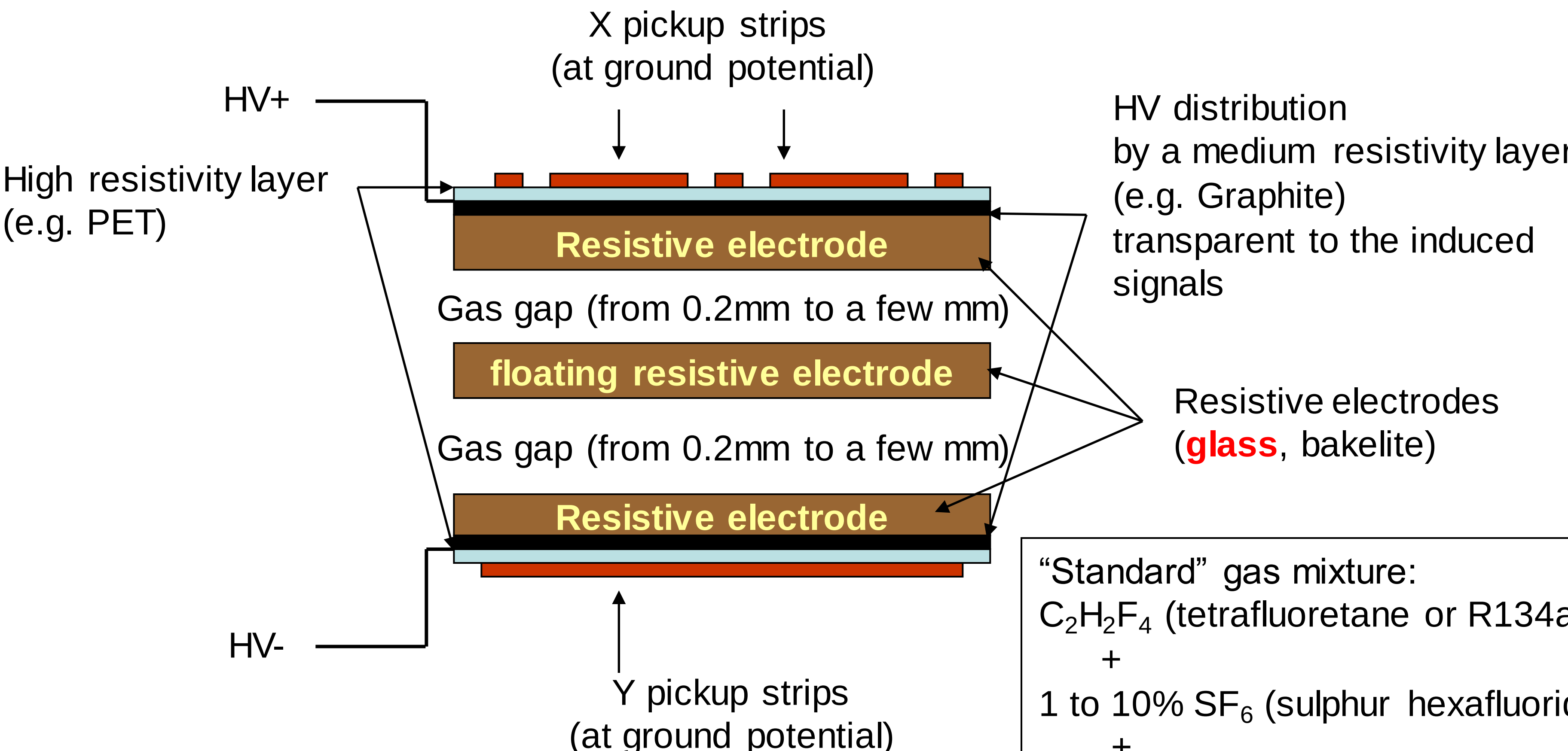
- 10’ of detector physics
- 5’ of RPC technology

} by special request of some RPC fans

- RD51: TOFtracker and animal RPC-PET
- NEULAND: a fast neutron TOF detector

10' of detector physics – basic structure

Many variations allowed



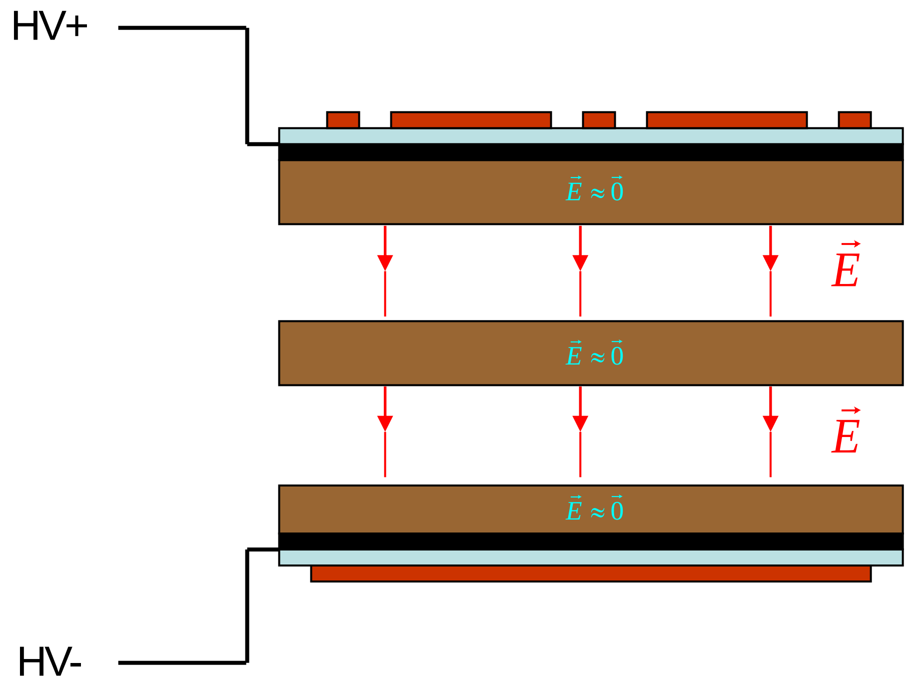
"Standard" gas mixture:
$C_2H_2F_4$ (tetrafluoretane or R134a)
+
1 to 10% SF_6 (sulphur hexafluoride)
+
0 to 5% C_4H_{10} (isobutane)

The current is limited by the resistive electrodes: no sparks by construction

⇒ very safe detector, although limited to low particle rates (~2kHz/cm^2)

⇒ excellent efficiency (99%), time (~50 ps) and position resolution (~100μm)

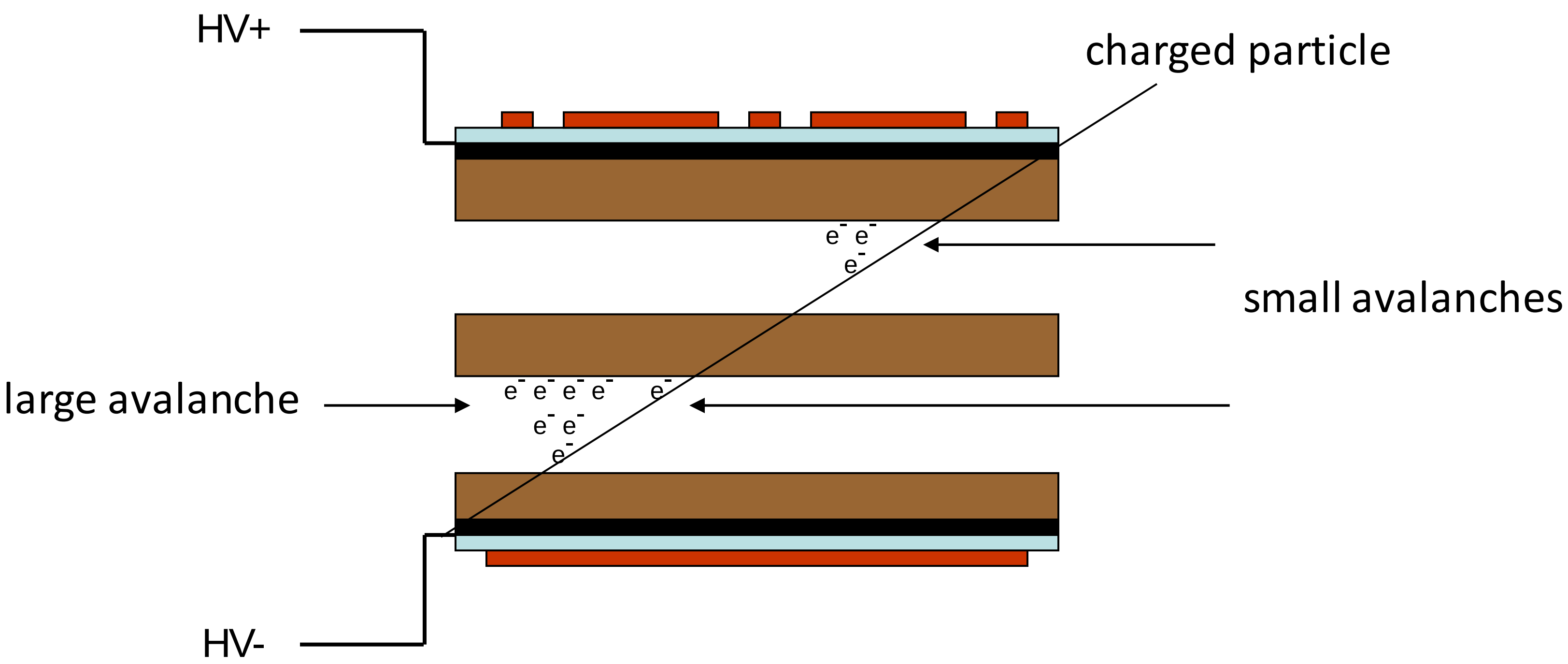
10' of detector physics – applied field



In steady-state the E field is expelled from all materials and appears only on the gas gaps

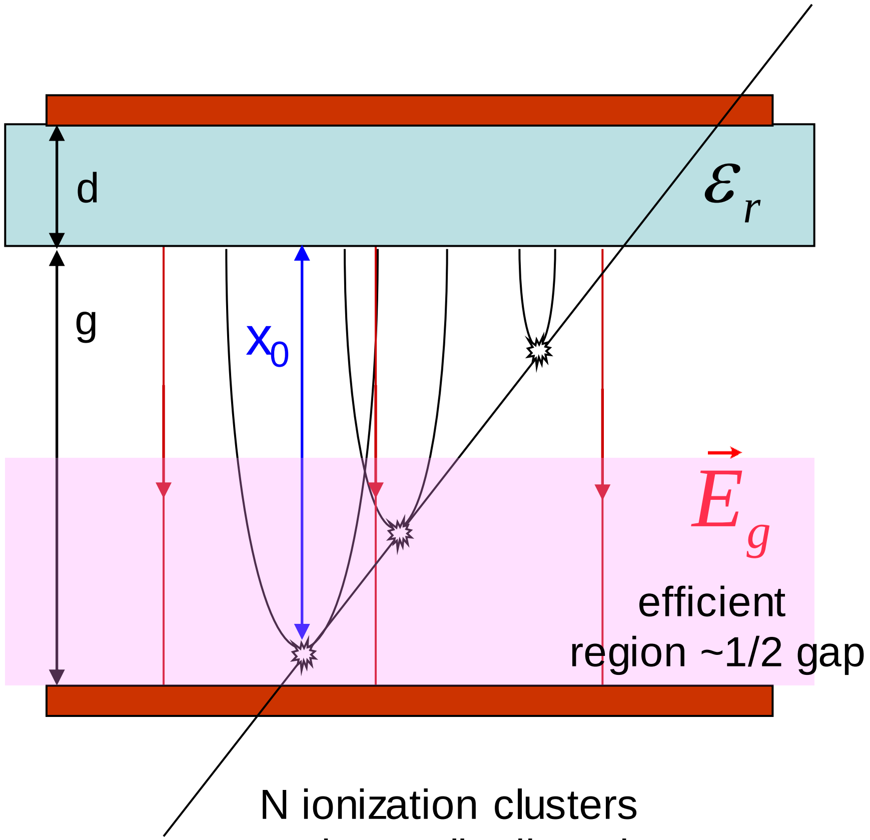
The floating electrode assumes the potential that equalizes the current on both gaps

10' of detector physics – gas multiplication



Charged particles ionize the gas. The released electrons are accelerated by the applied field and multiply in avalanche.
The final avalanche size depends exponentially on the position of the initial electron. Only ionizations that take place far from the anode contribute to efficiency ⇒ single gap efficiency 75% to 90% ⇒ several gaps needed

10' of detector physics – gas multiplication



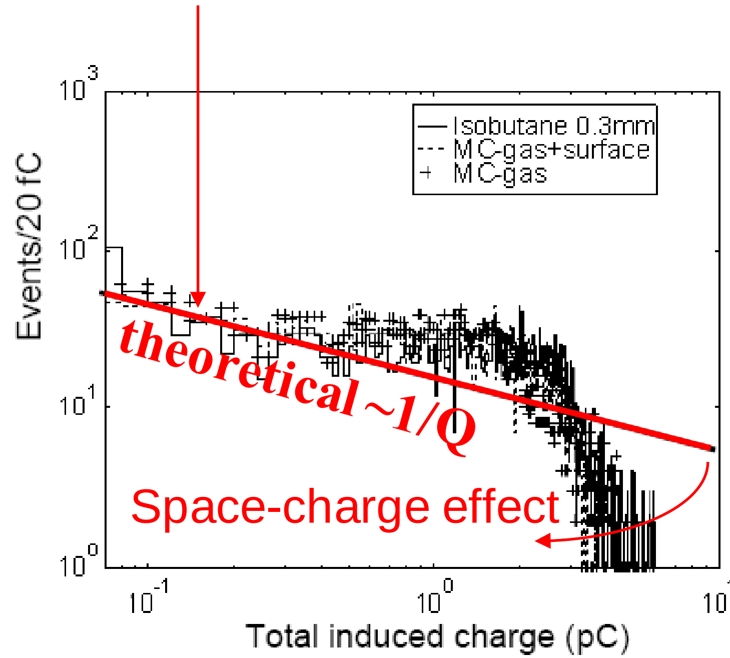
N ionization clusters
Poisson-distributed

primary ionization linear density λ

There must be at least 1 cluster
in the efficient region

$$q_e = q_{e0} e^{\alpha x_0}$$

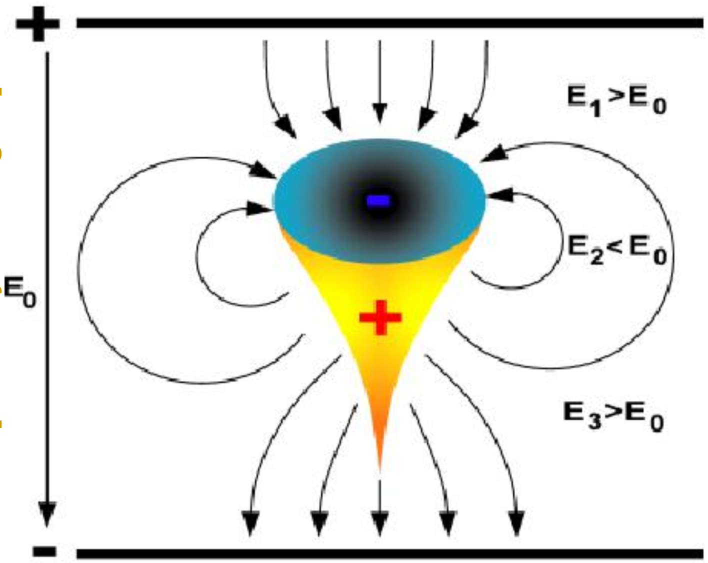
Generated charge/cluster depends exponentially on x_0 (α=ionizations/cm)



Space-charge effect saves the day
FUNDAMENTAL to RPC operation

10' of detector physics – space-charge effect - streamers

[courtesy W.Riegler]



Higher field: anode (forward) streamer

Lower field: safe, controls the avalanche

Higher field: cathode streamer
(but needs a secondary process)

Streamers are triggered when the space-charge field becomes comparable to the applied field:

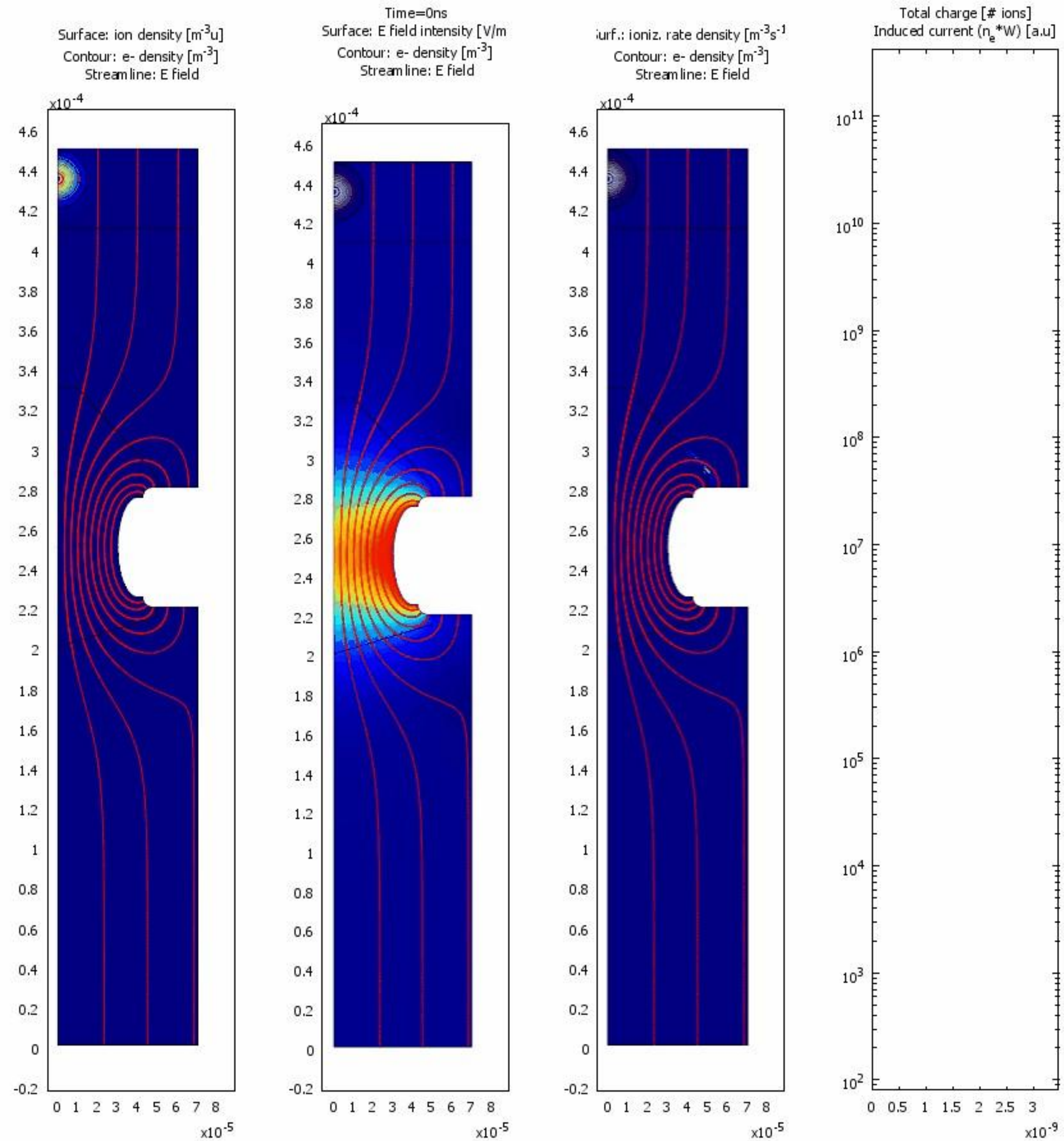
a charge-dominated,
geometry-dependent process.

10' of detector physics – space-charge effect – streamers

Avalanche and streamer simulation by finite elements in a GEM (contribution to RD51)

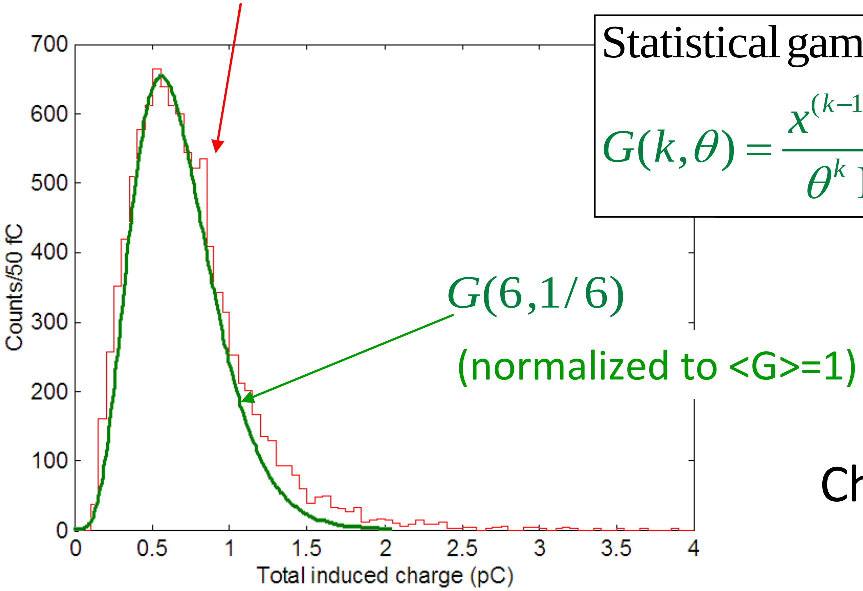
In metallic detectors there will be a spark, not just a streamer. This is a HUGE advantage of RPCs.

Very non-linear process. Response of RPCs to particles other than MIPs is quite unknown.



10' of detector physics – gas multiplication – charge spectrum

Measured single MIP charge spectrum in a 4 x 0.3 mm gap RPC, standard gas



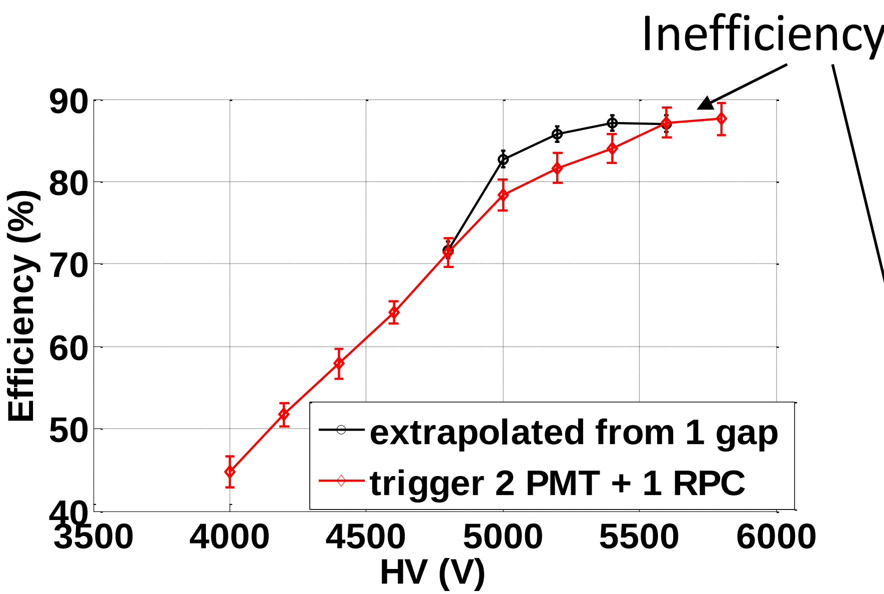
Statistical gamma distribution

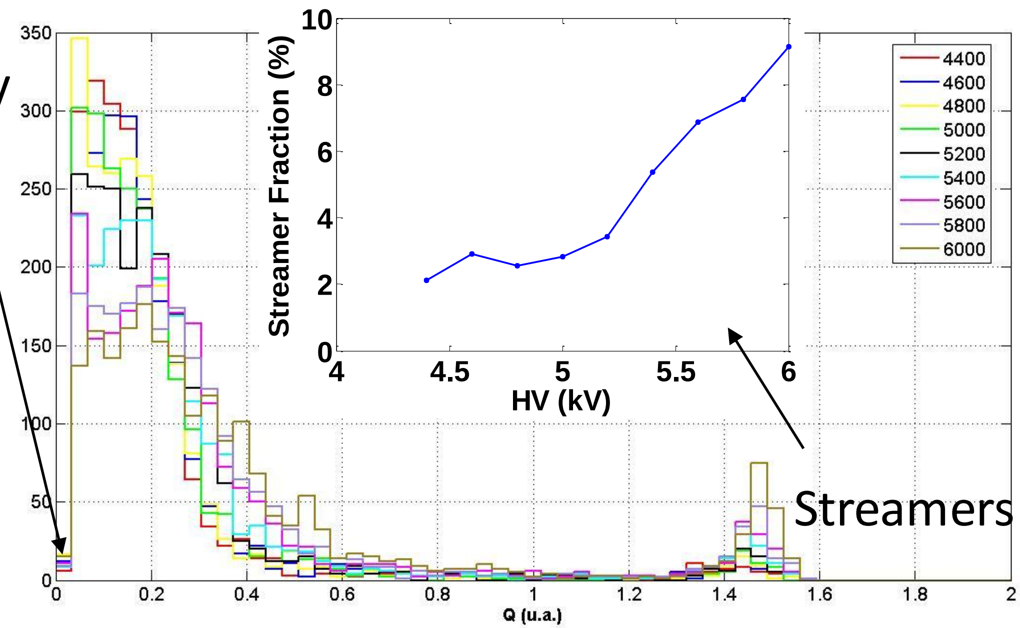
$$G(k,\theta) = \frac{x^{(k-1)} e^{-x/\theta}}{\theta^k \, \Gamma(k)}$$

Empirical distributions.
No exact theory available.

Many gaps/many particles
-> n-fold convolution of
single-gap distributions.

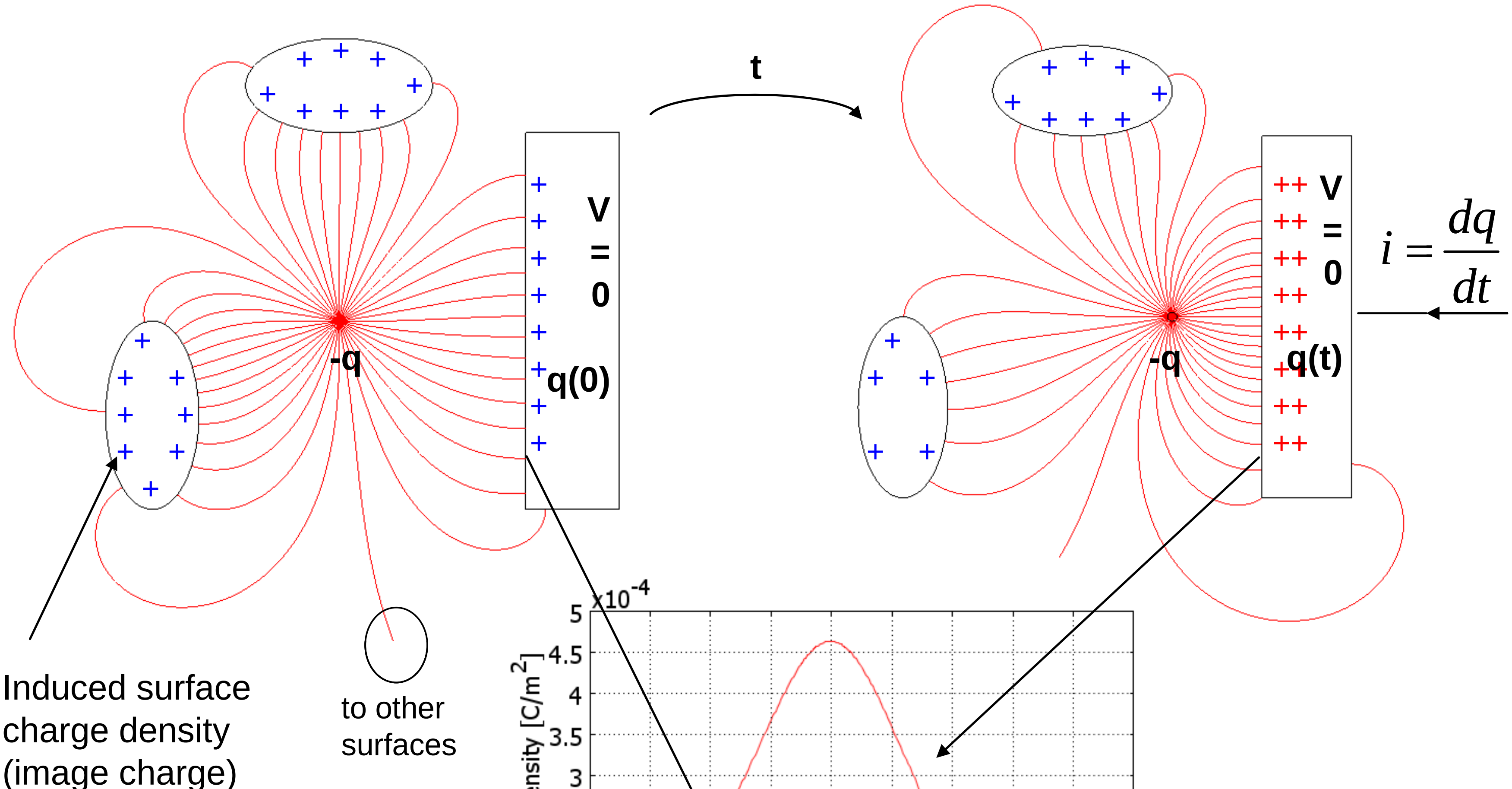
Charge spectrum for 2 gaps, pure R134a (AUGER)

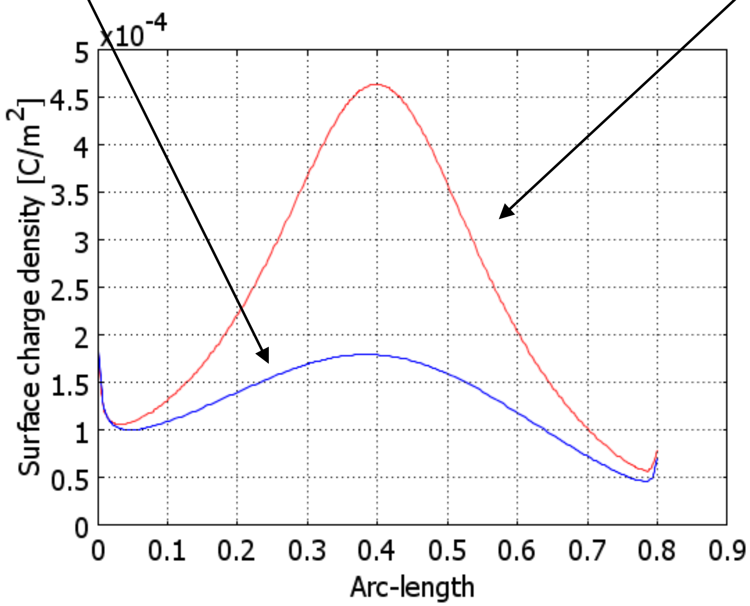




10' of detector physics – charge induction

Pure electrostatics

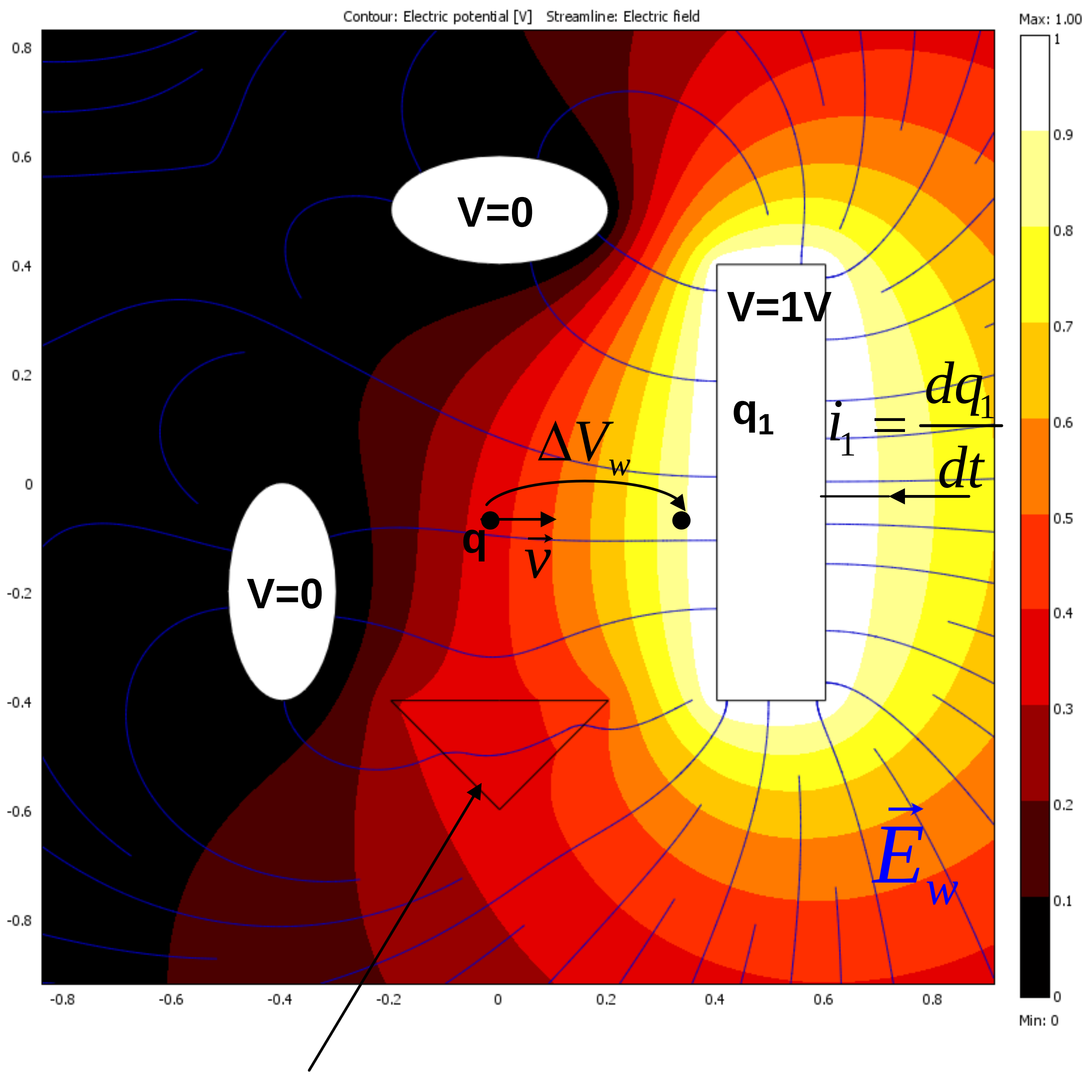




Charge induction is determined by the MOVEMENT of charges (not by collection at the electrodes)

10' of detector physics – charge induction

Pure electrostatics



Dielectrics DO matter.

To find the induced charges and currents to one electrode apply 1 V to this electrode and 0 V to the others, generating the weighting potential V_w and the weighting field E_w.

$$\Delta q_1 = -q\Delta V_w / 1V$$

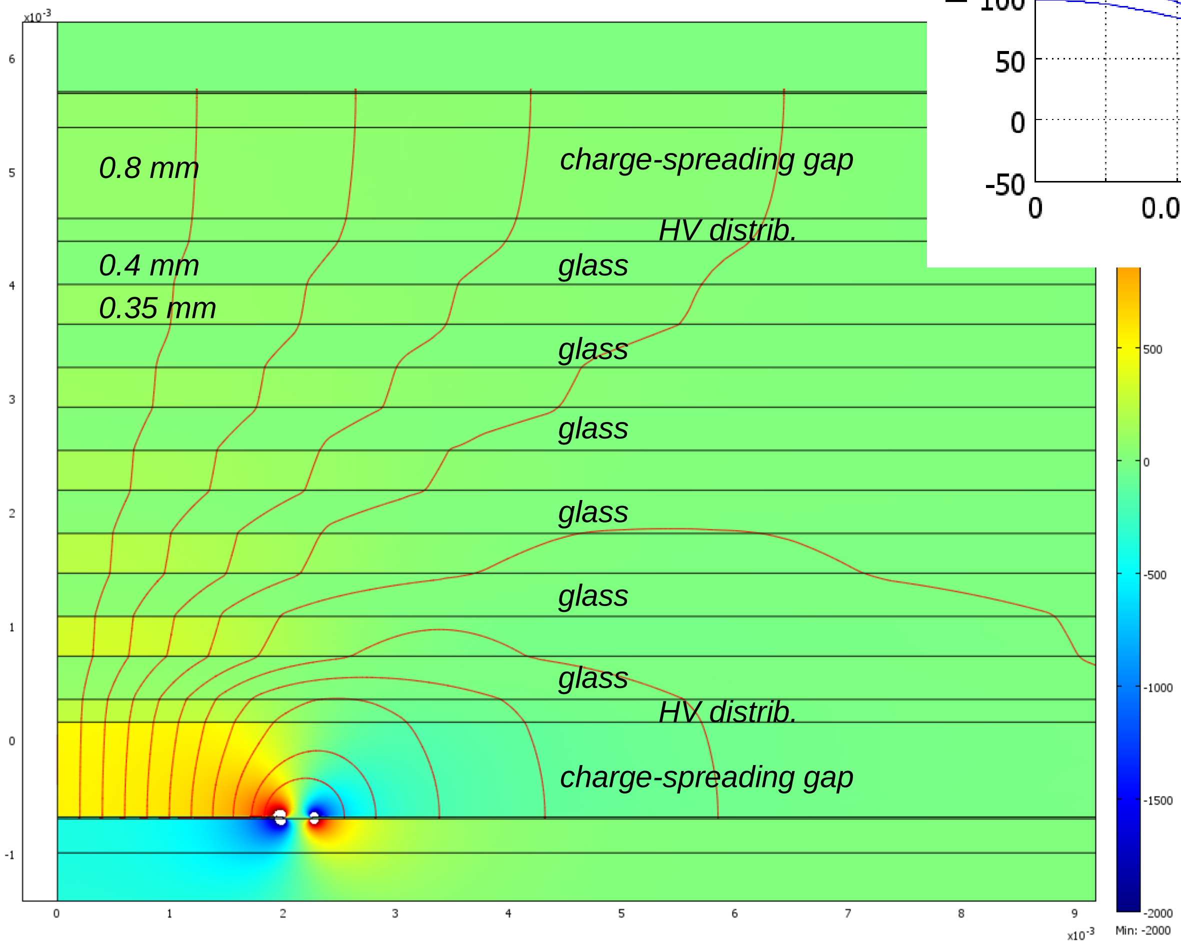
$$i_1 = q\vec{v} \cdot \vec{E}_w / 1V$$

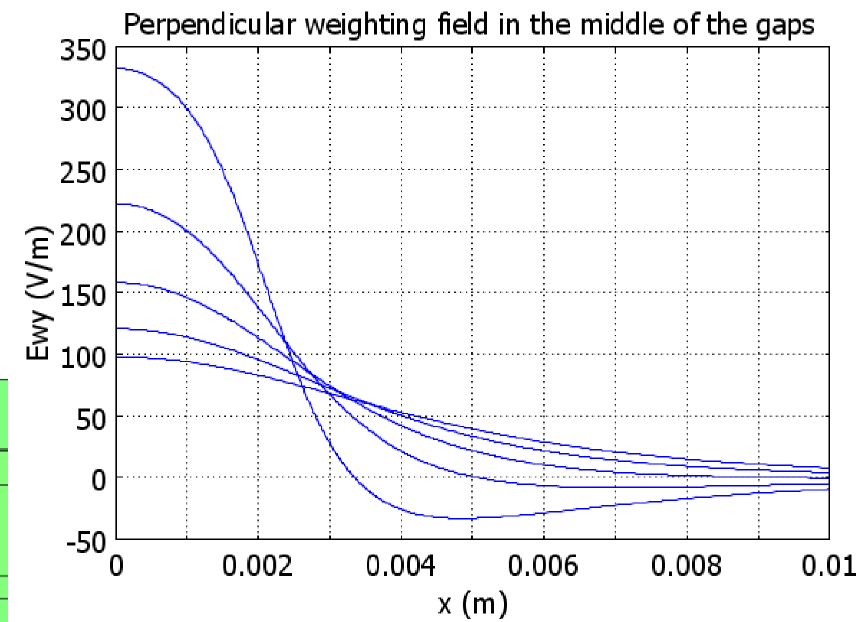
There are plenty of ways to do such electrostatics calculations.

10' of detector physics – charge induction

Example from animal RPC-PET / TOFtracker

Weighting field lines and perpendicular weighting field intensity for the RHS of a 4 mm strip



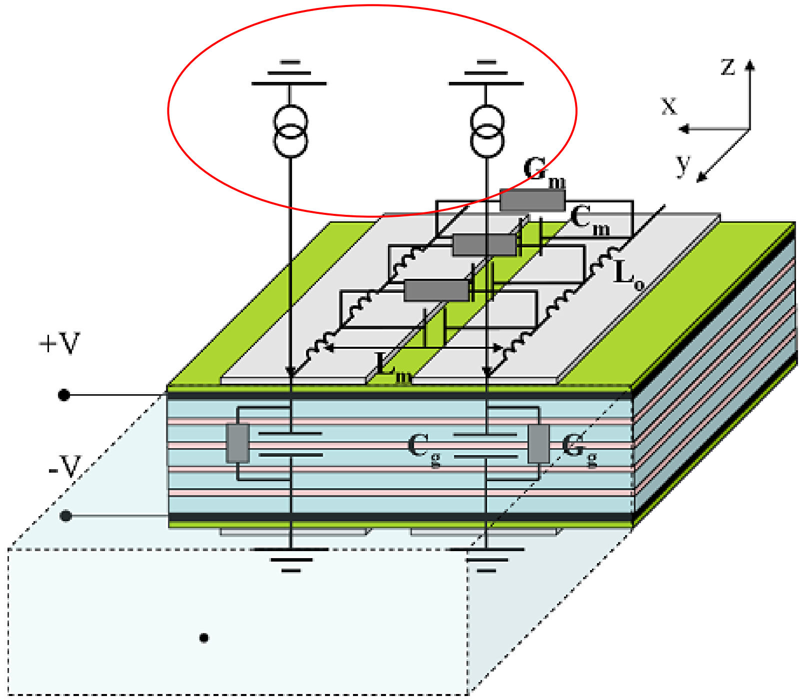


Every gap produces its own very distinct induction profile.

In the end all gaps will fire and the effective induced charge profile will be an EbyE weighted average.

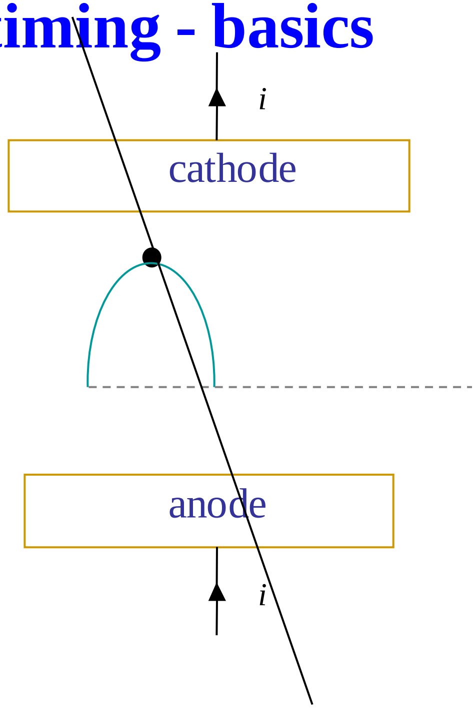
10' of detector physics – signal propagation

Avalanches can be seen as current sources feeding the electrodes



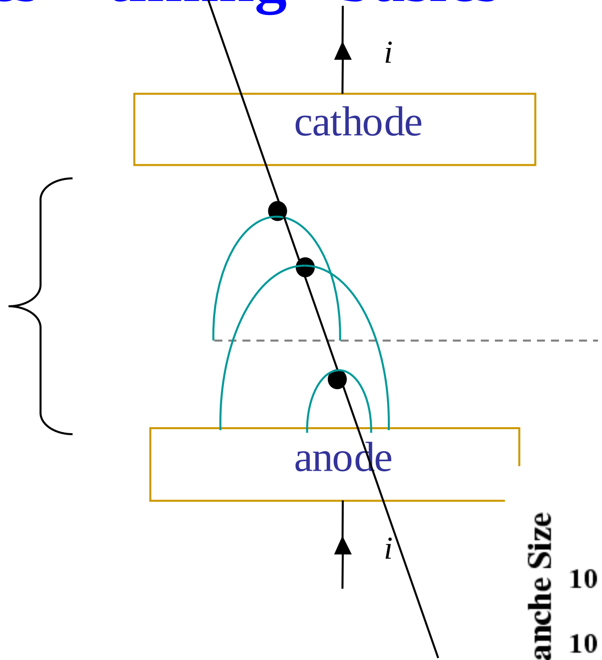
- The system of electrodes is a multi-conductor transmission line.
- Accurate theory exists. Only electrostatics needed!
- Complicated problem: crosstalk. Problem eased for readout with slow charge amplifiers (crosstalk doesn't transfer any net charge)

10' of detector physics – timing - basics



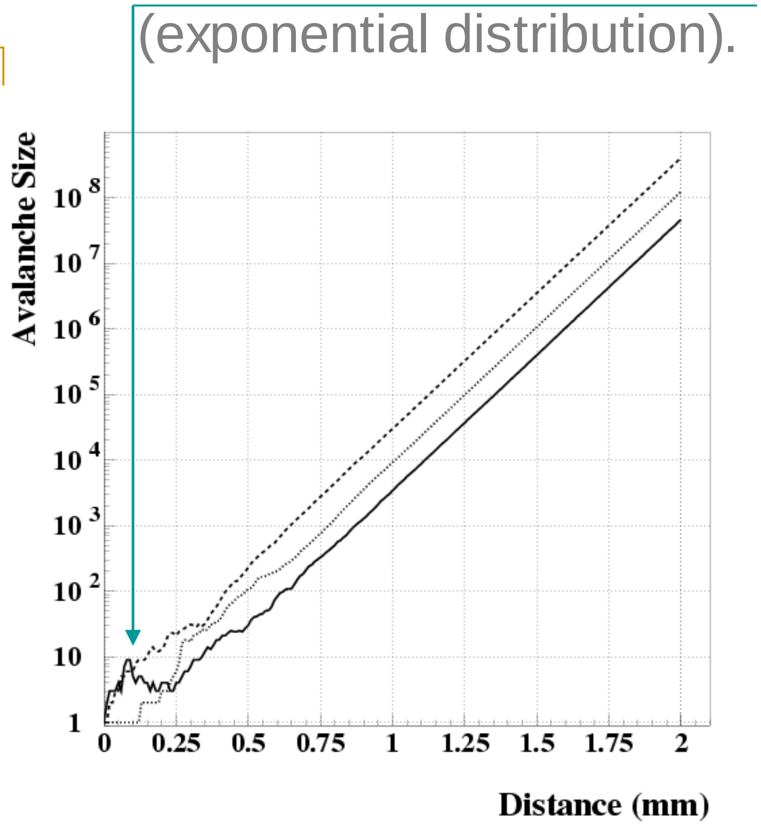
Detection level <u>independent</u> from the cluster position
⇒
<u>exact timing</u>
(If no primary statistics or avalanche statistics)

10' of detector physics – timing - basics



Several clusters (Poisson distribution)

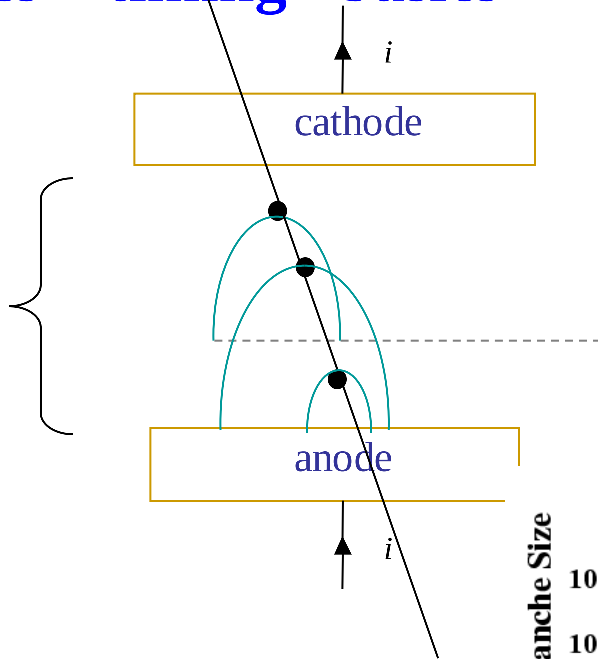
Time needed to reach a given current depends on avalanche growth statistics (exponential distribution).



[Werner Riegler, Elba, 2003]

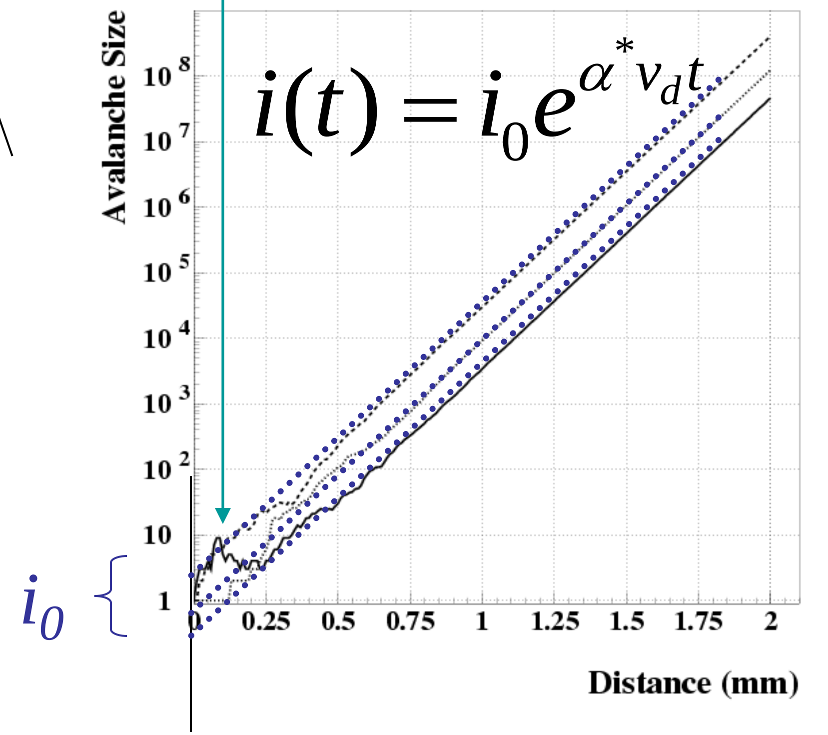
10' of detector physics – timing - basics

Several clusters
(Poisson distribution)



Time needed to reach a given current depends on avalanche growth statistics (exponential distribution).

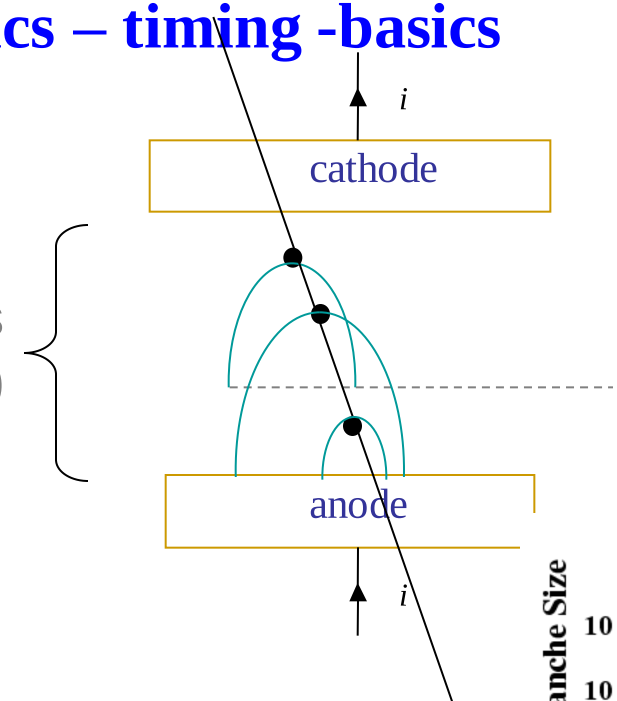
$$i(t) = i_0 e^{\alpha^* v_d t}$$



10' of detector physics – timing -basics

analytical model

Several clusters
(Poisson distribution)



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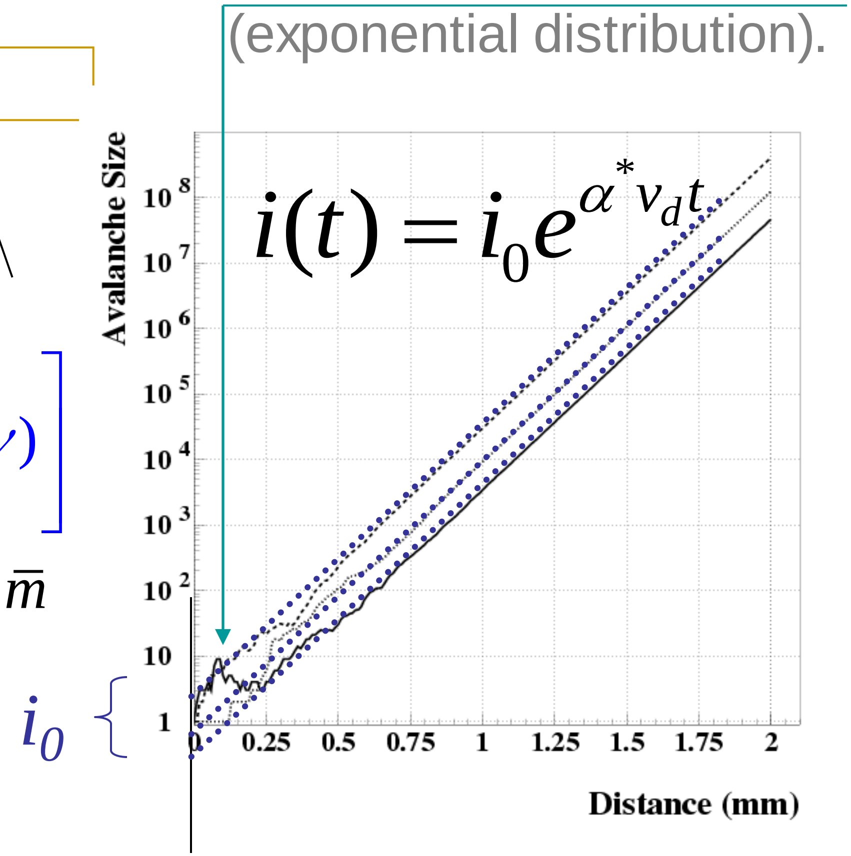


$$i(t) = i_0 e^{\alpha^* v_d t}$$

$$p(i_0) = i_{e^-} e^{-r n_0} \left[e^{-r\nu} \frac{r\sqrt{n_0}}{\sqrt{\nu}} I_1(2r\sqrt{n_0 \nu}) + \delta(\nu) \right]$$

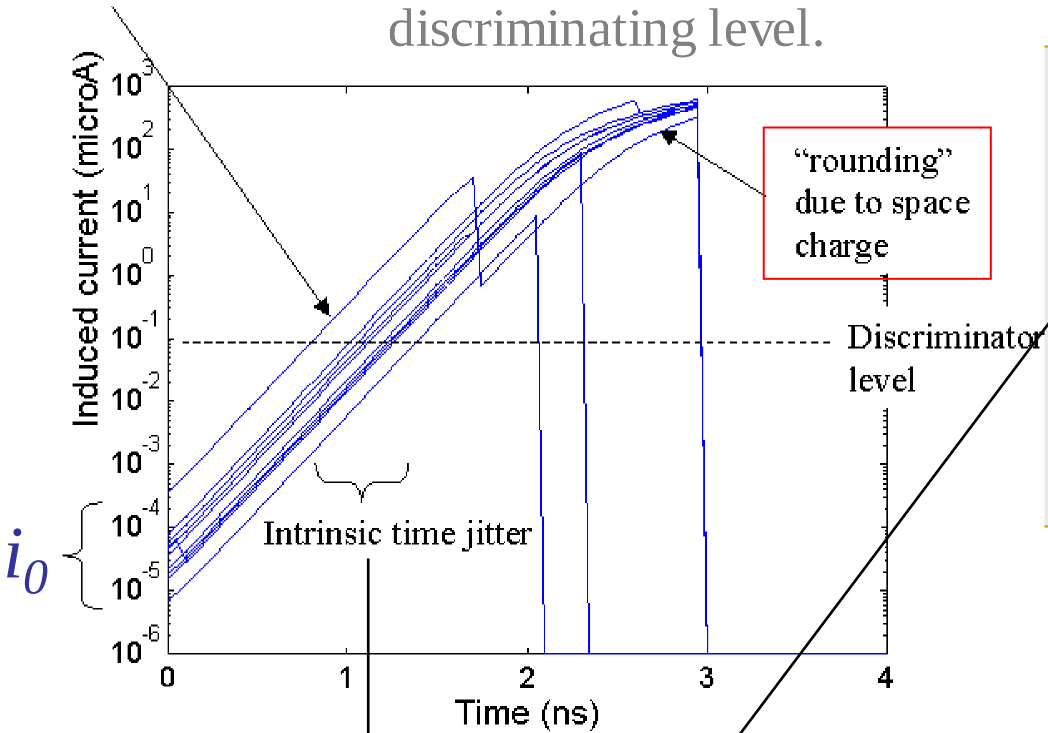
$$\alpha^* = \alpha - \eta; \quad k = \eta / \alpha; \quad r = 1 - k; \quad \nu = m / \bar{m}$$

i_{e^-} = current of a single drifting electron

[Mangiarotti, Fonte and Gobbi, RPC2003]

10' of detector physics – timing - analytical model

The i_0 distribution is translated into a time distribution by action of the discriminating level.



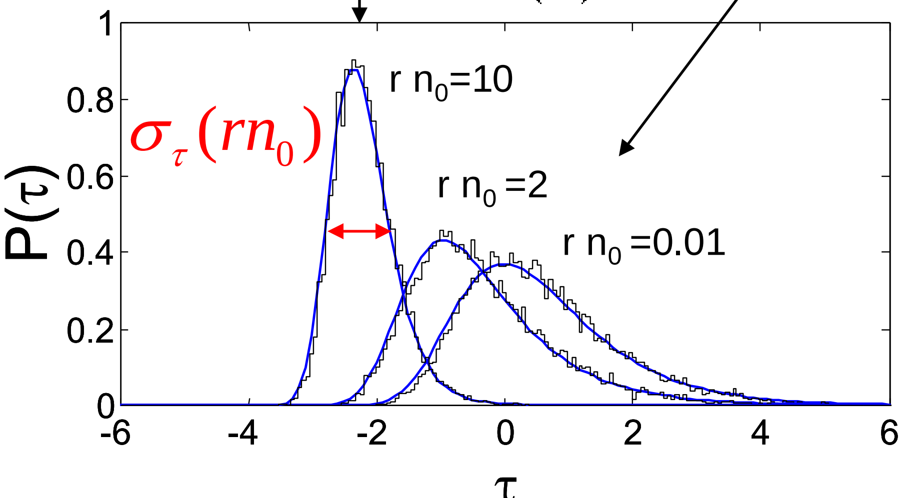
[MAN04]

Single-cluster

$$p(\tau) = e^{(\tau_t-\tau)-\exp(\tau_t-\tau)} \frac{rn_0 I_1\left(2\sqrt{rn_0 e^{\tau_t-\tau}}\right)}{\left(e^{rn_0}-1\right)\sqrt{rn_0 e^{\tau_t-\tau}}}$$

$$t = \frac{1}{\alpha^* v_d}\tau \Rightarrow \sigma_t = \frac{1}{\alpha^* v_d}\sigma_\tau(rn_0)$$

Basic time scale: ~100 ps.



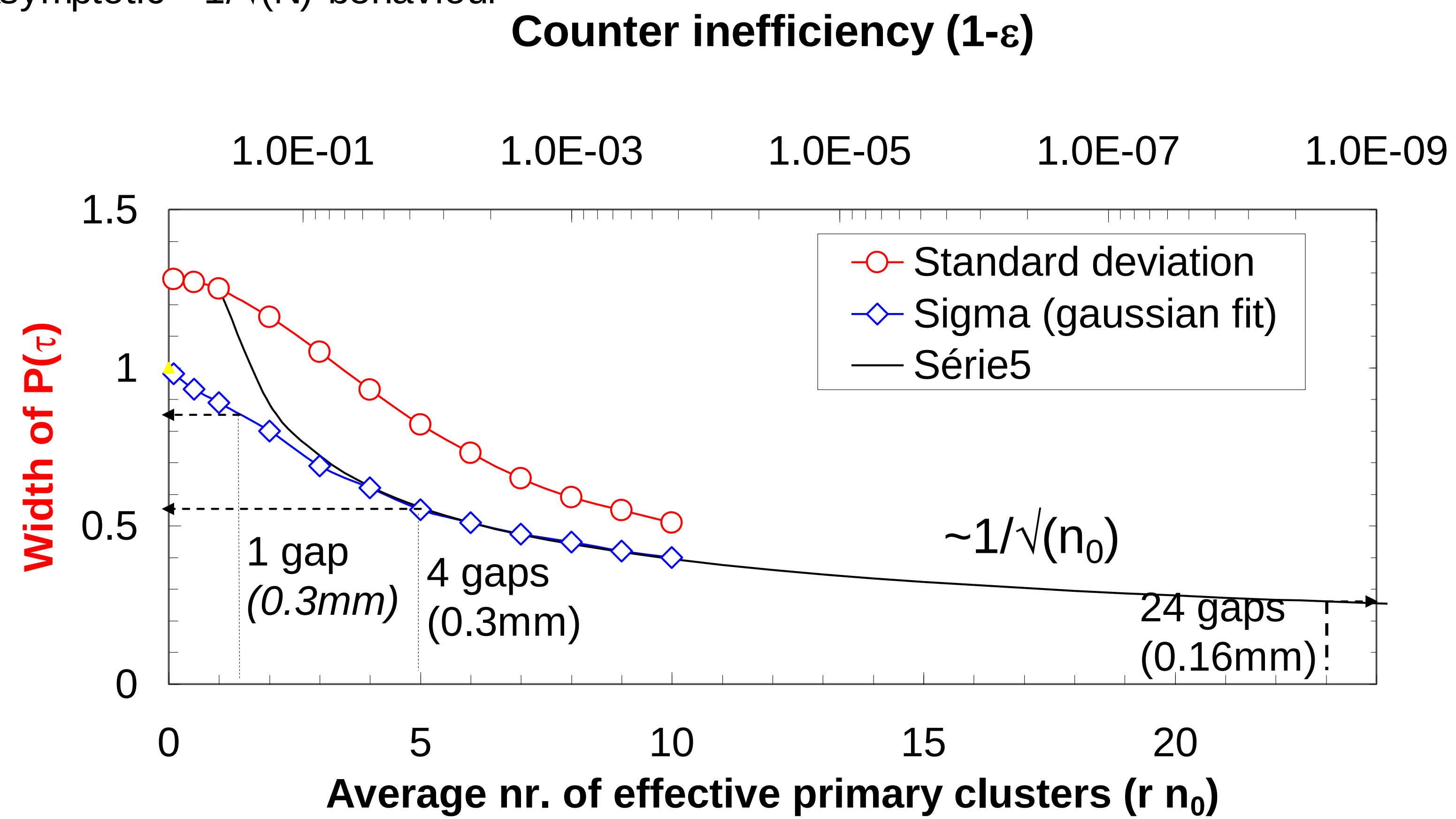
The timing depends essentially only on 2 parameters:

- -linearly on $1/(\alpha^* v_d)$ = 1/ionization rate
- -on the average number of effective primary clusters ($r\,n_0$)

10' of detector physics – timing - analytical model

Universal curves

- The resolution is a function of the inefficiency only
- scale given by $1/\alpha v \cong 100$ *ps*
- Asymptotic $\sim 1/\sqrt{(N)}$ behaviour



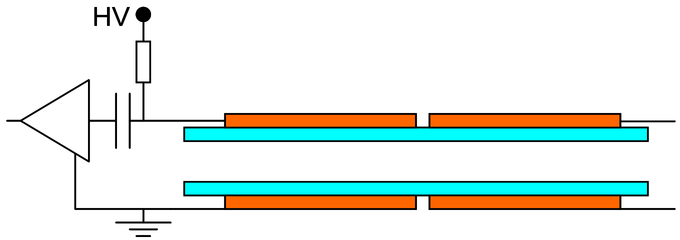
Observable resolution should be somewhat better, as the time somewhat correlates with charge and can be corrected. Maybe this is just the trivial electronics slewing correction?

Summary detector physics

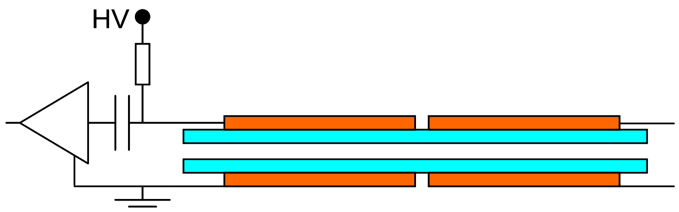
- Charge spectra, streamer fraction: very difficult to model. Must rely on empirical observation and general experience. Gases: hidrofluorocarbons + SF_6 + ?
- Response to non-MIPs poorly understood.
- Efficiency, time resolution reasonably understood.
- Induction and propagation of current on the electrodes is determined by electrostatics only.

5' of detector technology

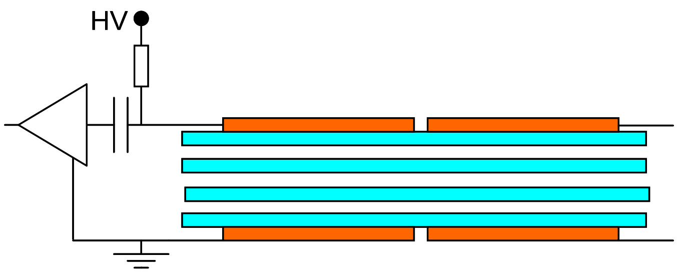
Many detector-electrode configurations are possible.



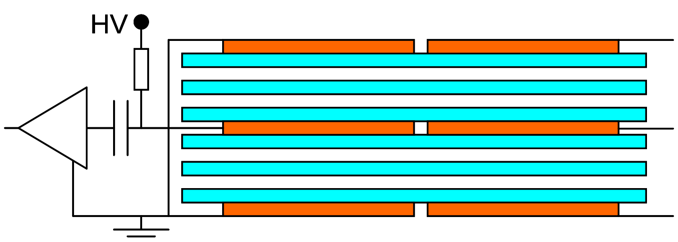
Asymmetric wide-gap (typ. 2 mm)



Asymmetric narrow-gap (typ. 0.3 mm)



Asymmetric multigap [Williams et al., 1996]



Symmetric multigap

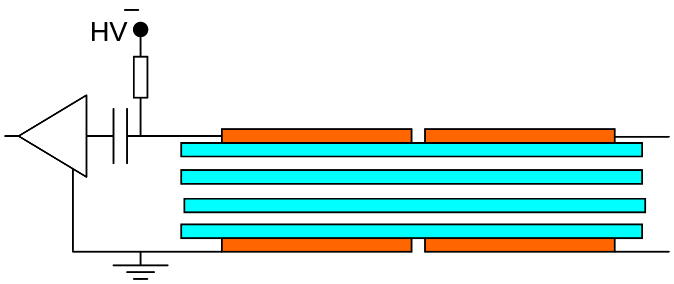
and several other combinations…

Both sides can be readout (opposite polarity). Electrode shapes arbitrary.

Anger-like signal sharing possible (via electrostatics, not optics)

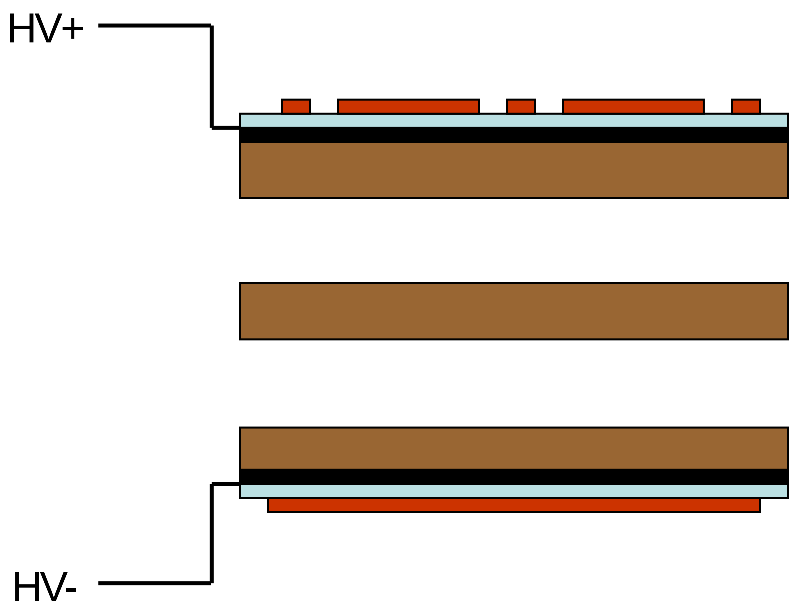
5' of detector technology

HV directly on the electrodes



(HADES)

HV via a resistive layer, insulated from the electrodes.



(all our new projects)

5' of detector technology

Gas tightness, HV insulation. Some approaches:

Outer box + feedthroughs (FOPI, HADES, animal RPC-PET)

Problem: zilions of feedthroughs
+ long o-ring to make gas-tight.

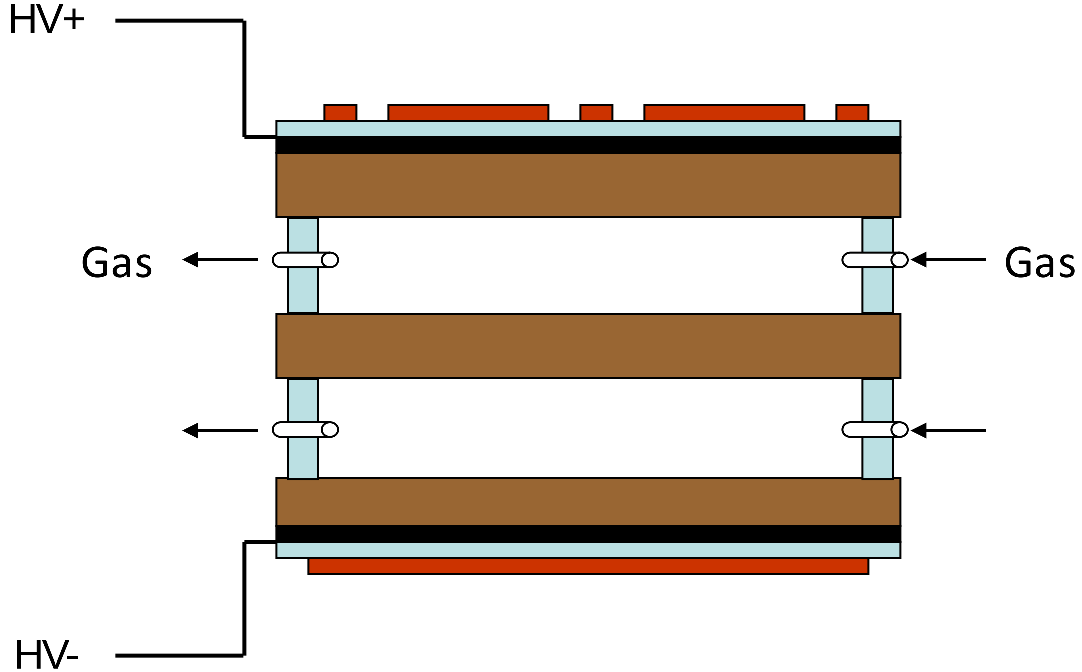
Advantages: fully serviceable.
HV insulation independent from gas tightness.

5' of detector technology

Gas tightness, HV insulation. Some approaches:

Sealed gaps (ATLAS, CMS)

Problem: HV exposed to air and humidity.
Gas volume not serviceable.



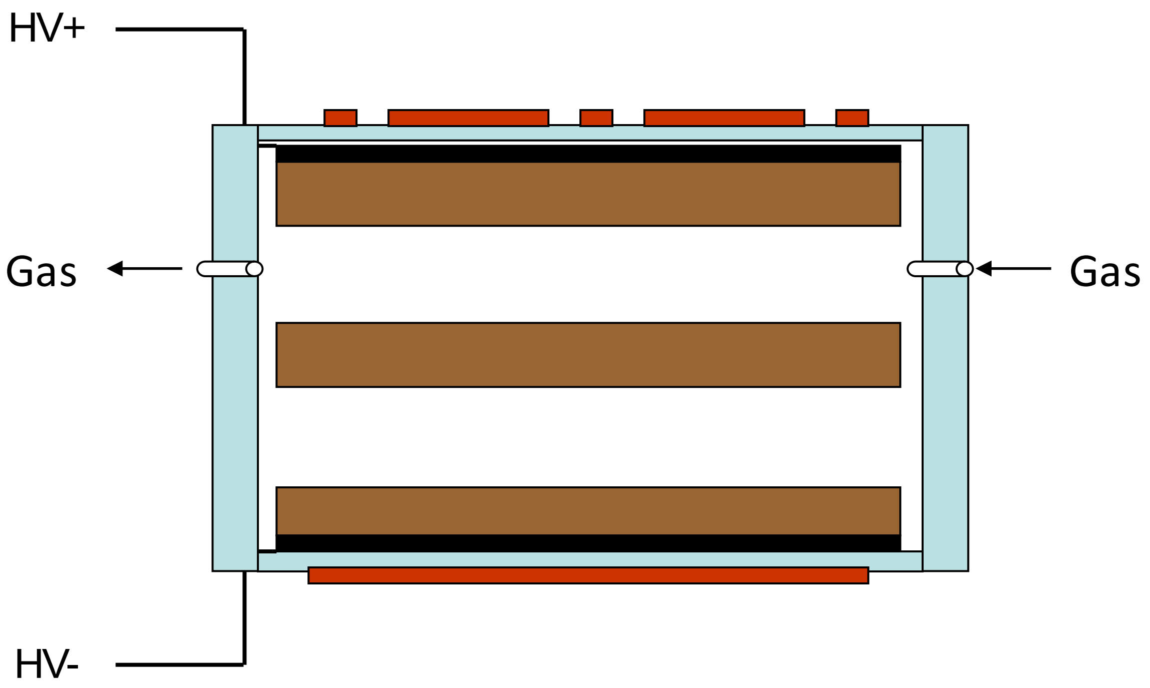
Advantages: gas problem solved.
HV insulation independent from gas tightness and serviceable.
Electrodes independent from detector

5' of detector technology

Gas tightness, HV insulation. Some approaches:

Sealed box (OPERA veto, AUGER?, NEULAND, human RPC-PET)

Problem: not serviceable at all.

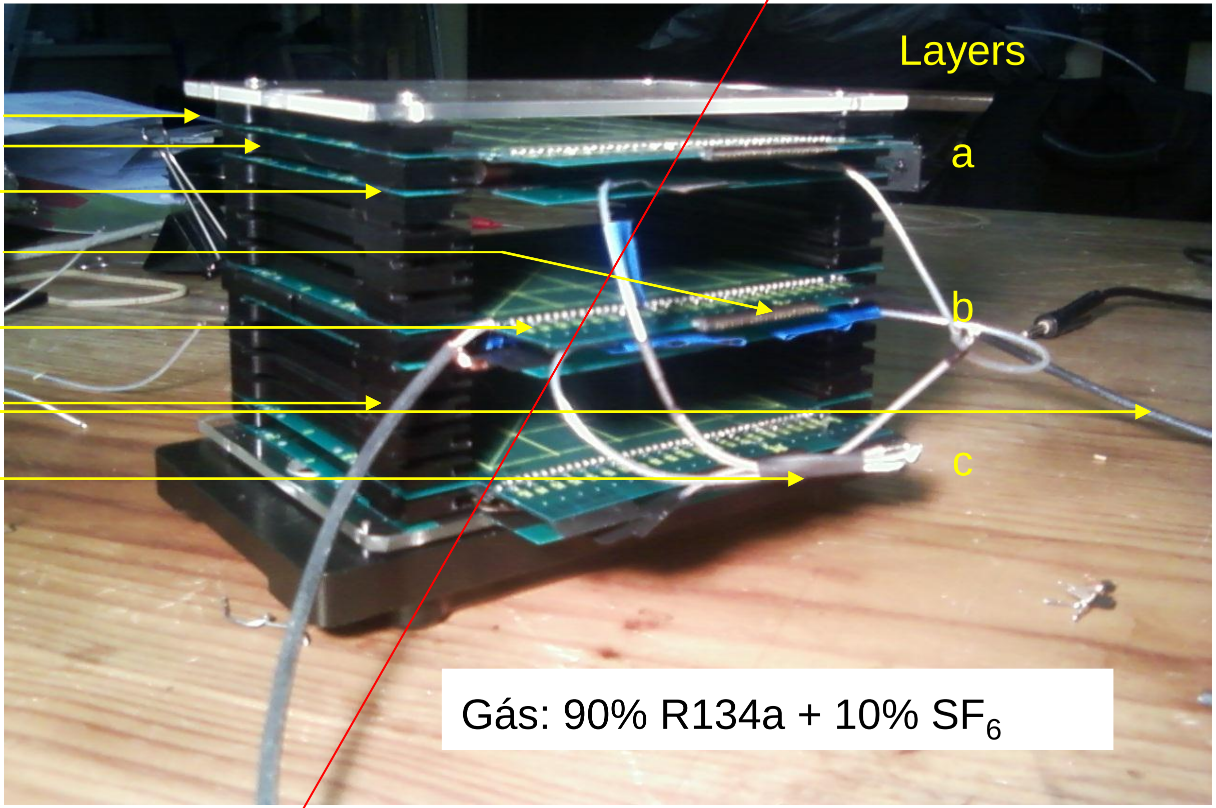


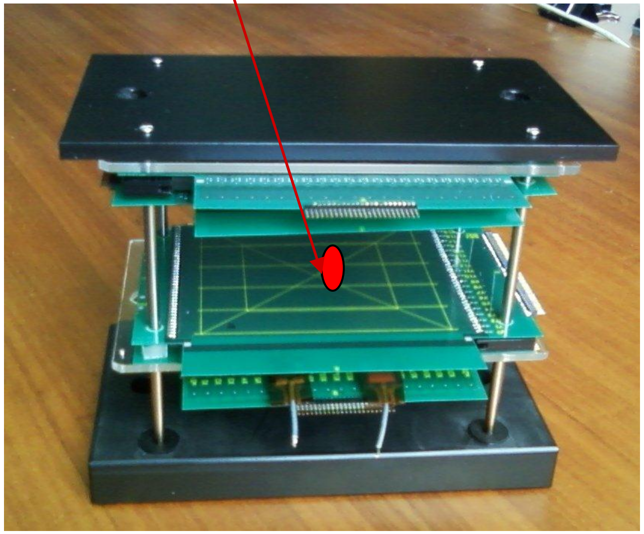
Advantages: Both problems solved. Electrodes independent from detector.

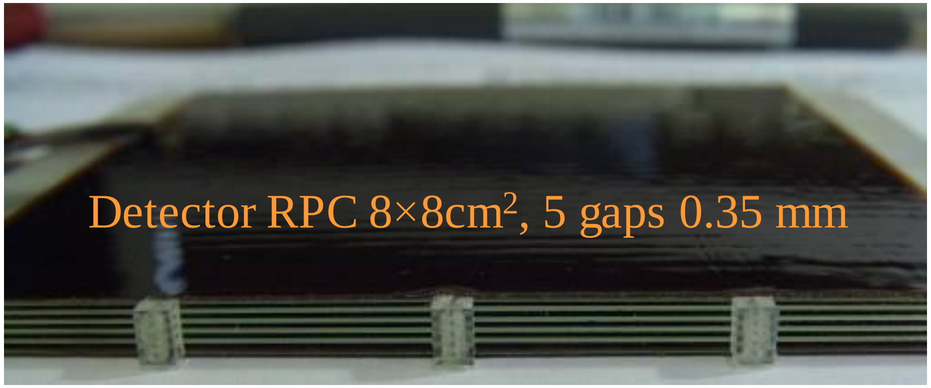
Summary of detector technology

Never quit.

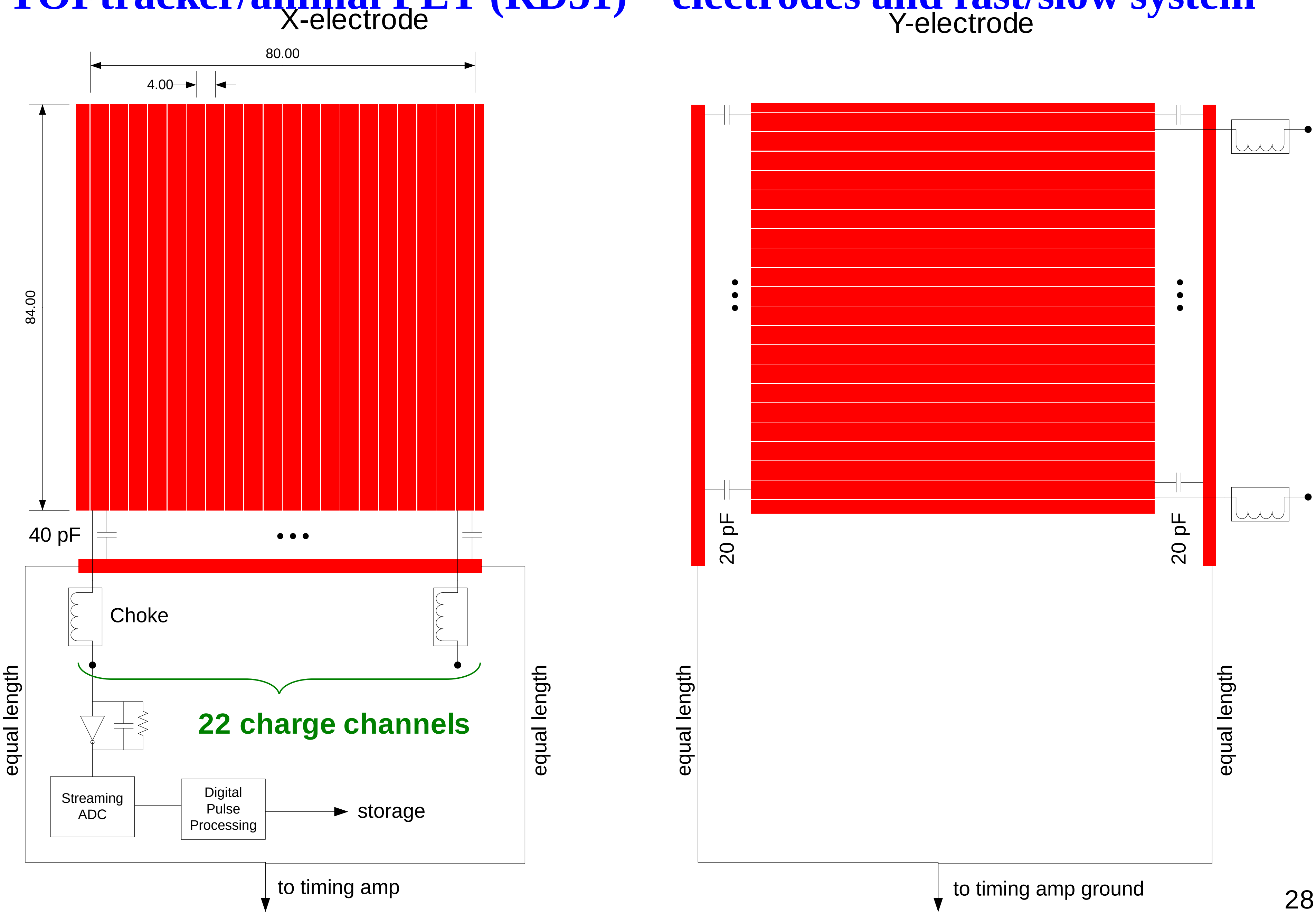
TOFtracker/animal PET (RD51) - configuration



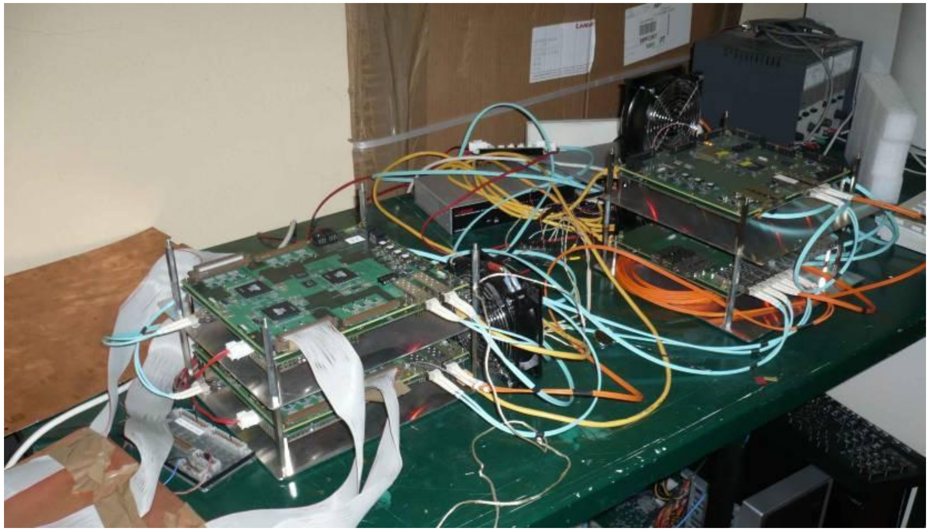




TOFtracker/animal PET (RD51) – electrodes and fast/slow system



TOFtracker/animal PET (RD51) – readout and DAQ



Discrete charge amps

Low noise but bulky

Would be more elegant with integrated electronics, e.g. APV25.

DAQ (from the upgraded HADES experiment)

196 ch, 40 MHz, streaming ADC + DSP

256 ch, 100 ps multihit TDC

TOFtracker/animal PET (RD51) – localization

Take the 3 strips with largest charge,

Q_{-1}, Q_0, Q_1.

Normalize and form the principal components

$S_1 = (Q_1 - Q_{-1})/\sqrt{2}/\text{sum}(Q)$

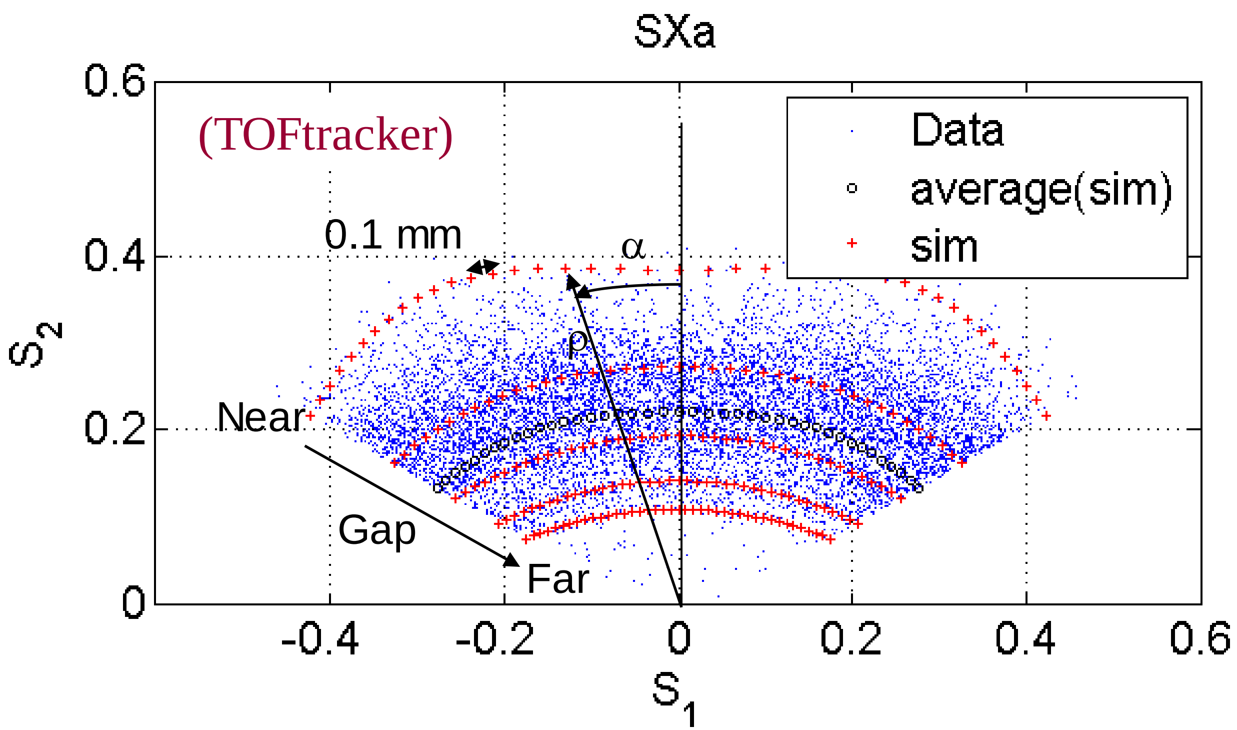
$S_2 = (Q_0/\sqrt{2} - (Q_{-1}+Q_1)/2)/\text{sum}(Q)$

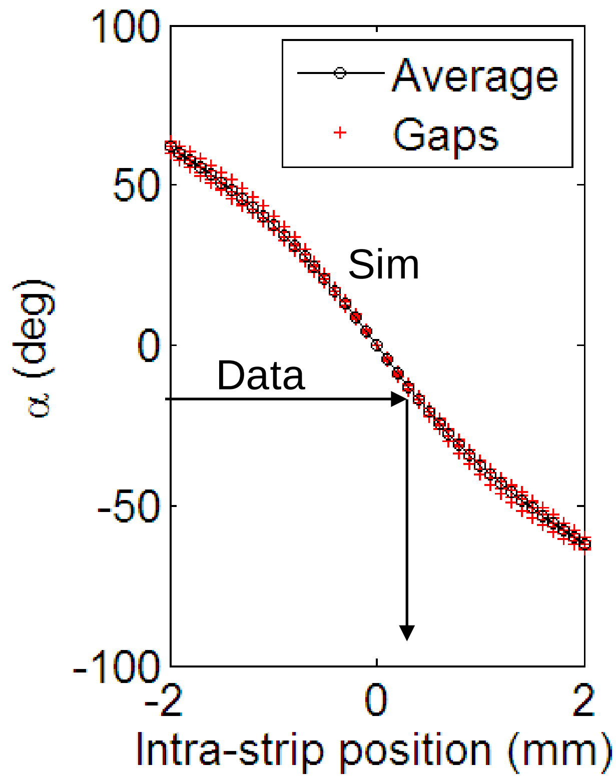
Then define

$\alpha = \text{atan}(S_1/S_2)$

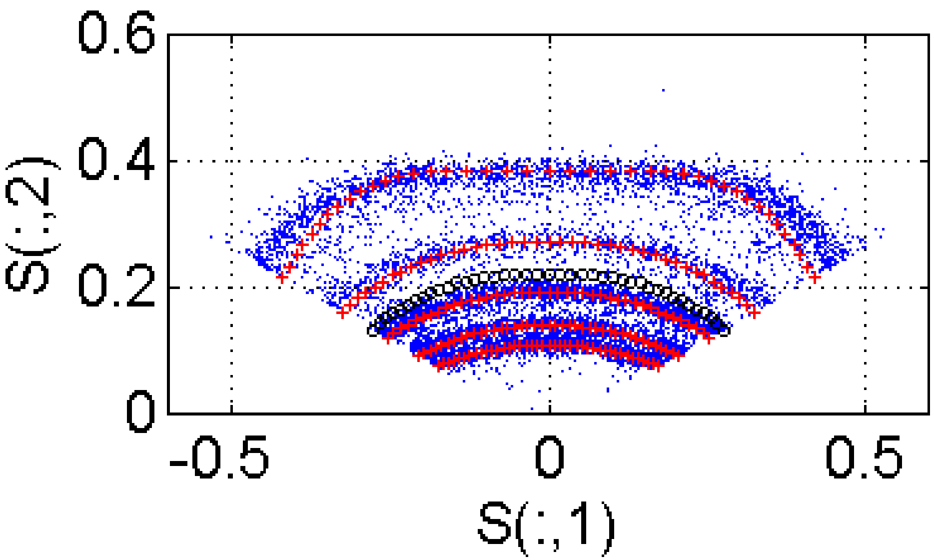
$\rho = \sqrt{(S_1^2+S_2^2)}$

α is related to the intra-strip position and ρ is a form factor related to the relative charge generated in each gap.





animal PET (RD51) – depth of interaction



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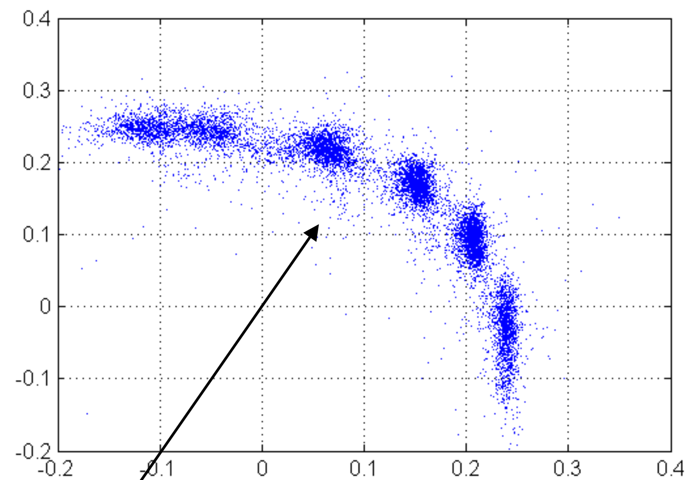
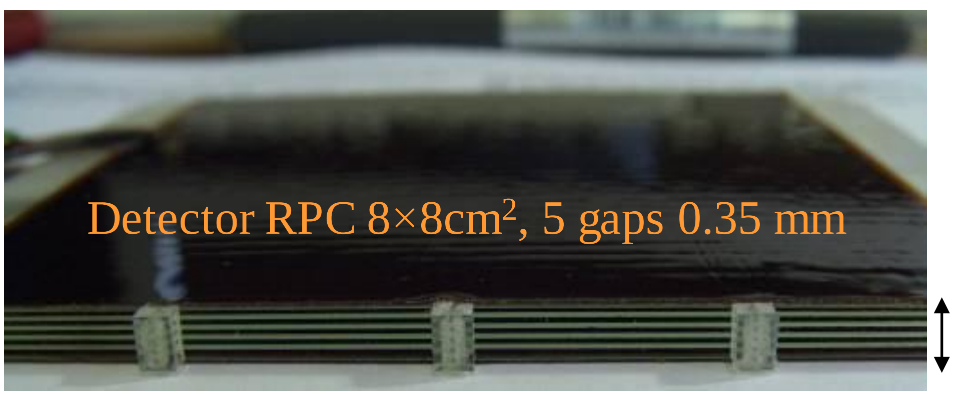
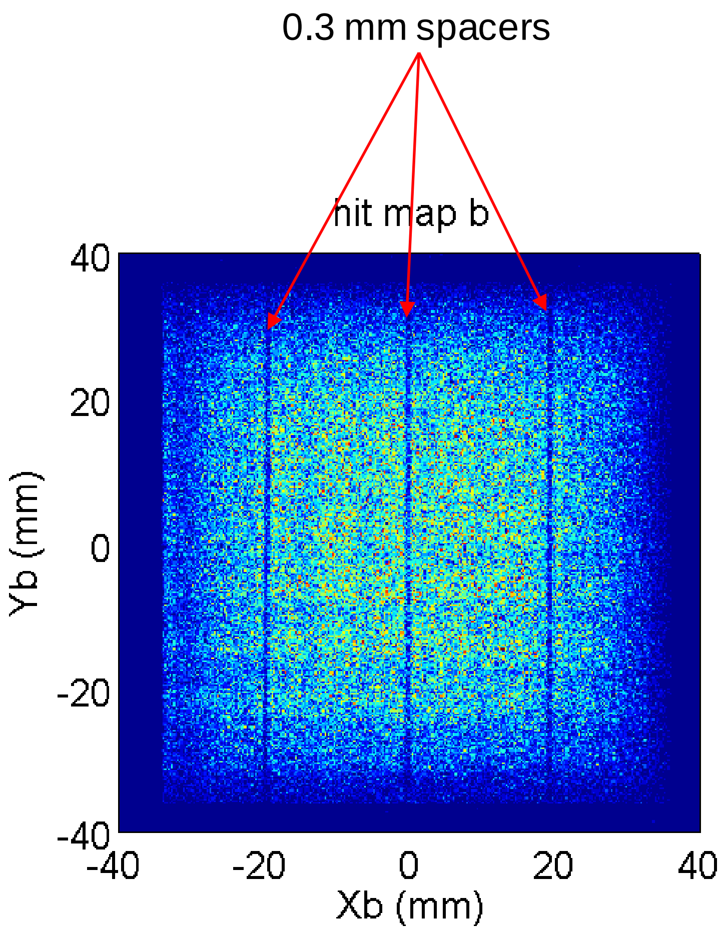
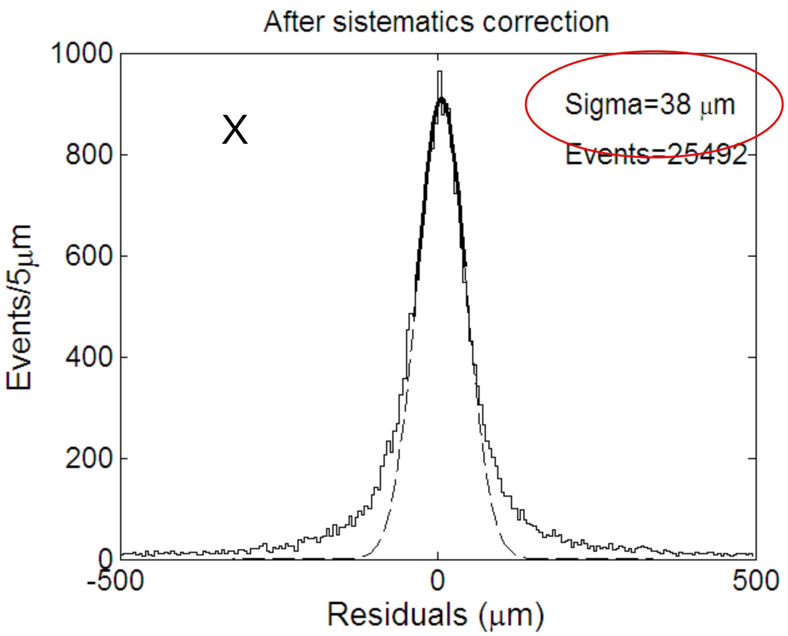


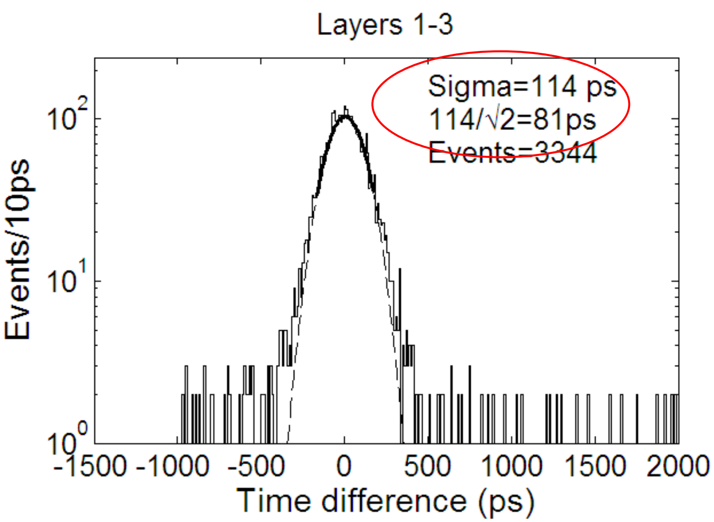
The 5 gas gaps clearly identified



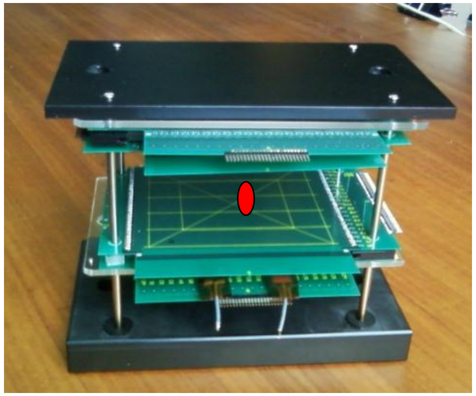
TOFtracker (RD51) – results



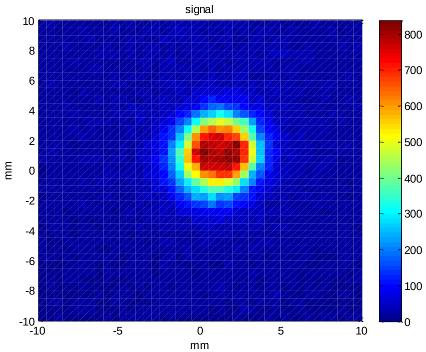


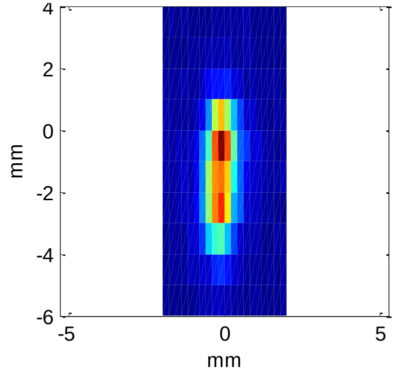


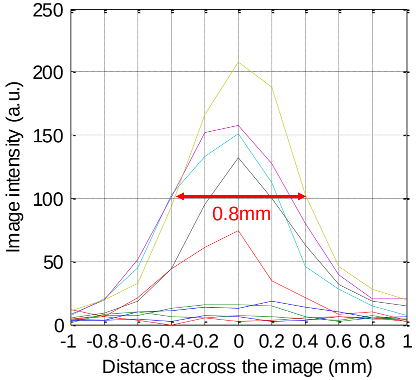
animal PET (RD51) – first results



First tests: projections of a flat disk source

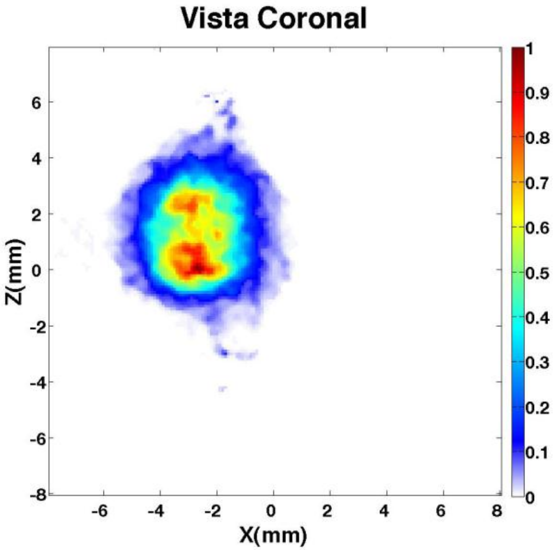


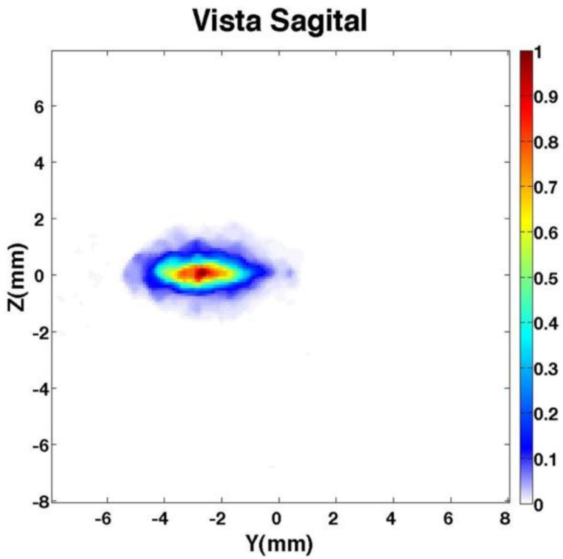


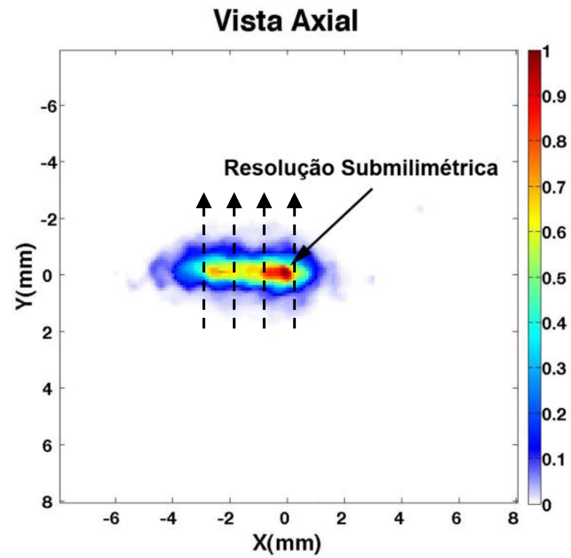


Profile across image (0.8mm FWHM)

Full area, all angles, MLEM reconstruction

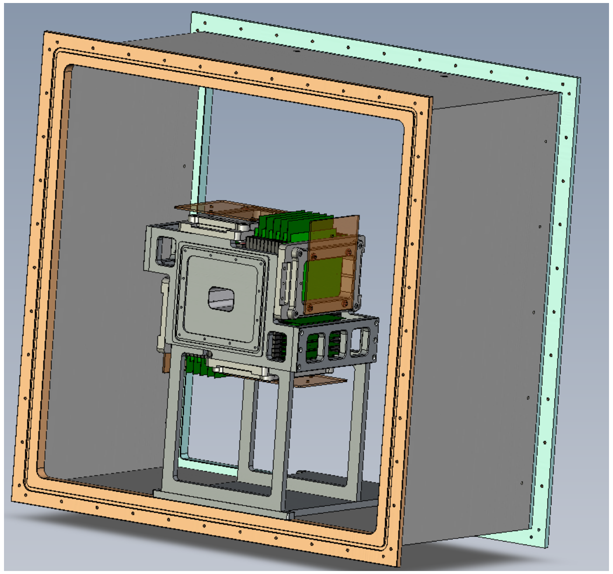




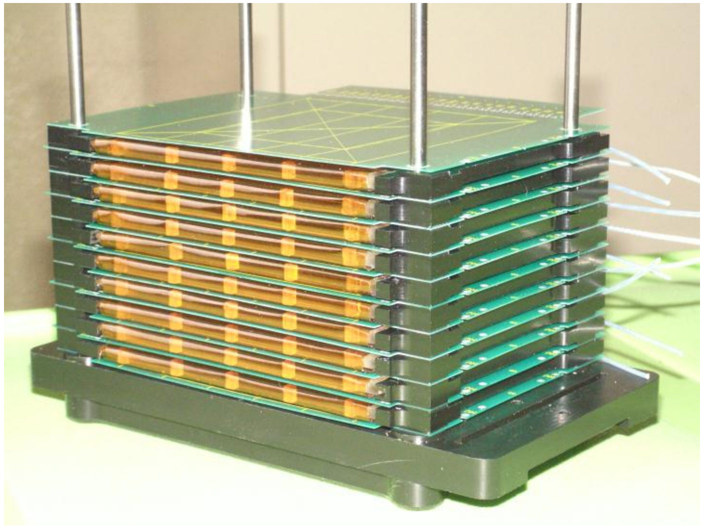


animal PET (RD51) – hopes

Full scanner (almost…)



Full head, now being commissioned
(x,y,z capability)



Very good resolution, median sensitivity and inexpensive
Great hopes for commercial development

NEULAND – simulation (by the CFNUL group)

Financed by PTDC2010

Fast neutron TOF detector for the future R3B experiment @ FAIR

2x2m^2

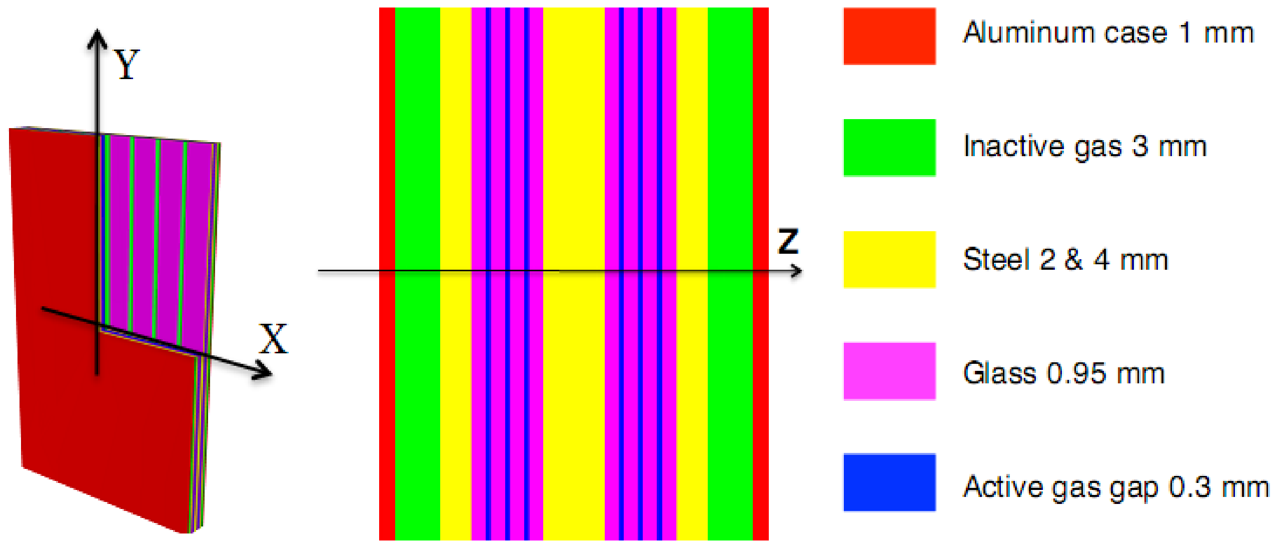
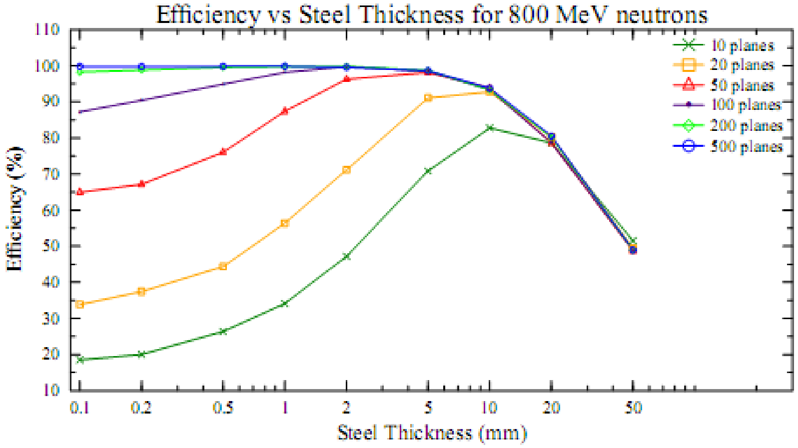


Figure 1: (Color online) Schematic view of the RPC design considered in the study of the performance of different converter material and converter thickness. The design is presented considering steel plates of 2mm thickness as converter. Taken from [5]

NEULAND – simulation (by the CFNUL group)

different converter materials were simulated



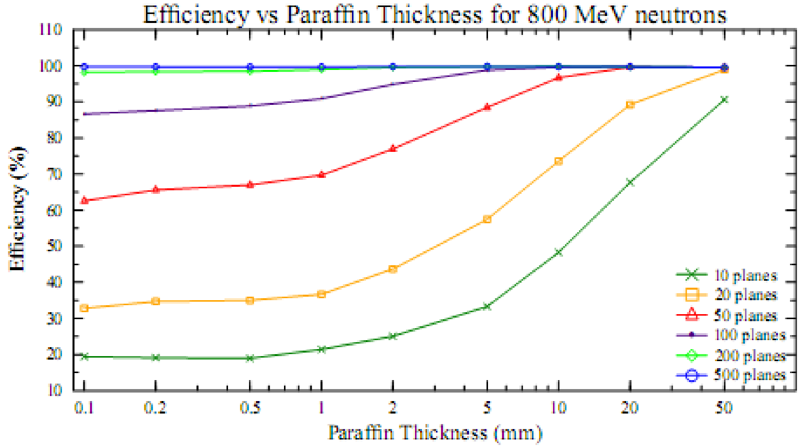


Figure 2: (Color online) Dependence of the detection efficiency on the thickness of the steel converter for several configurations with different number of detector planes.

Figure 3: (Color online) Dependence of the detection efficiency on the thickness of the paraffin converter for several configurations with different number of detector planes

NEULAND – simulation (by the CFNUL group)

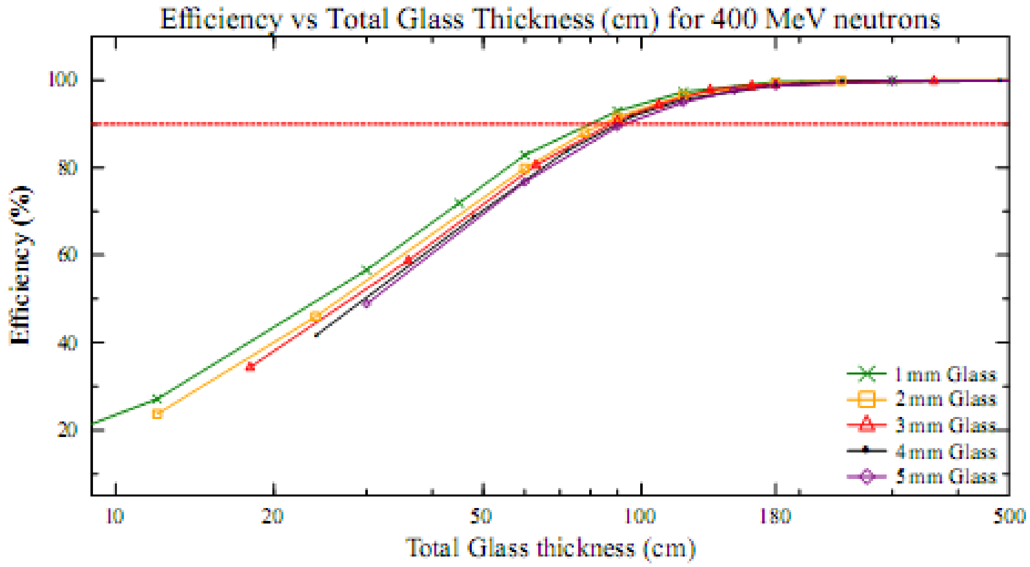


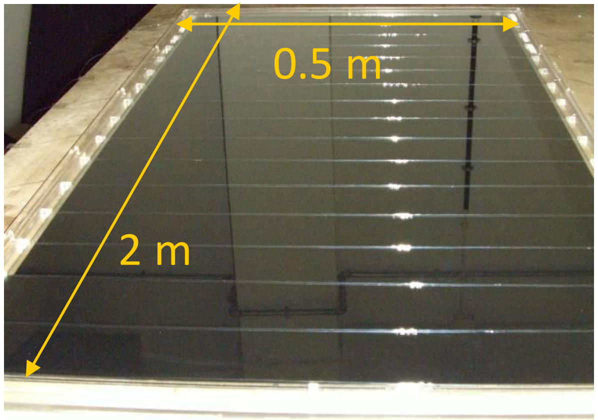
Figure 6: (Color online) Dependence of the detection efficiency on the total amount of glass contained in the RPC detector. This parameter seems to be the key factor for the neutron detection efficiency. Maximum efficiency can be reach with a total glass thickness of 180 cm.

After detailed studies it was concluded that for the detection of fast neutrons with sampling detectors essentially it only matters the total amount of matter!

-> the “ironless concept”: only 1.8 m of glass.

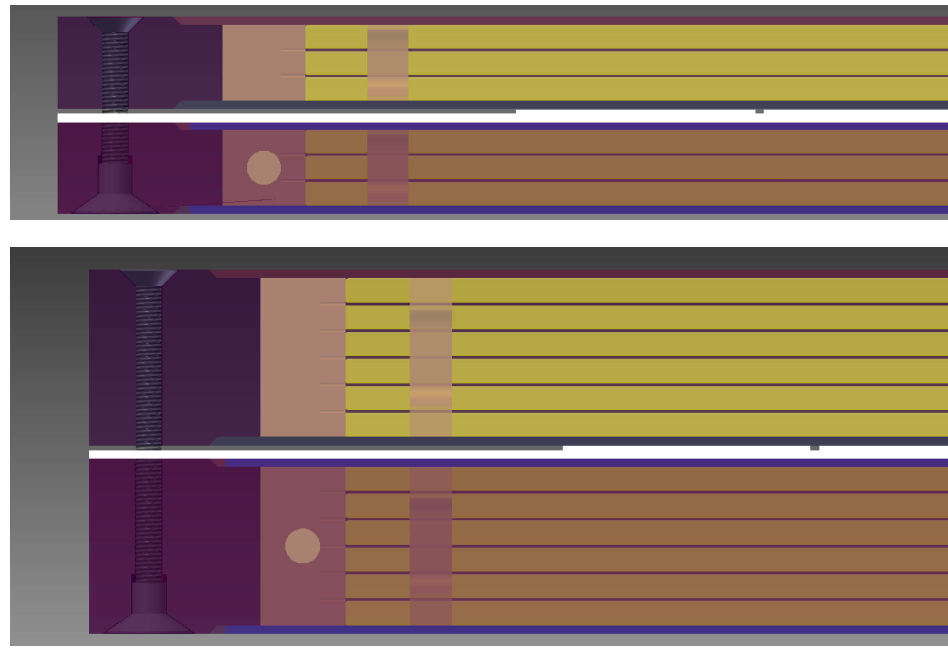
NEULAND – detector choices

Sealed box-type detectors (like AUGER's) in a slightly negative pressure (to press in the gaps)



In production in our new large-area milling machine

Two designs, 4-gap and 10-gap symmetric multigap RPCs
(because nobody knows how the RPCs will react to the neutrons)



Readout by 3x200 cm^2 strips with HADES' electronics & DAQ

NEULAND – beam setup

Beam test expected late Summer @ GSI