Micron-scale gas detectors

Simulations

Heed – Magboltz – Maxwell – Garfield

- Heed simulates ionisation patterns produced by charged particles and photons in a gas.
- Magboltz computes electron transport tables for nearly arbitrary gas mixtures: drift velocity vectors, diffusion tensors, Townsend and attachment coefficients.
- Maxwell is a finite element field calculation program.
- Garfield uses the above to trace electrons and ions in gas-based detectors, computing signals.

History

- These programs were developed for the simulation of centimeter-scale gas-based detectors with a spatial resolution of ~100 μm.
- They have been used with success for the simulation of TPCs, drift tubes, CSCs ...

- Since a couple of years, they are also used for smaller scale detectors – generally with less success.
- This talk discusses the background to the problems that are encountered.

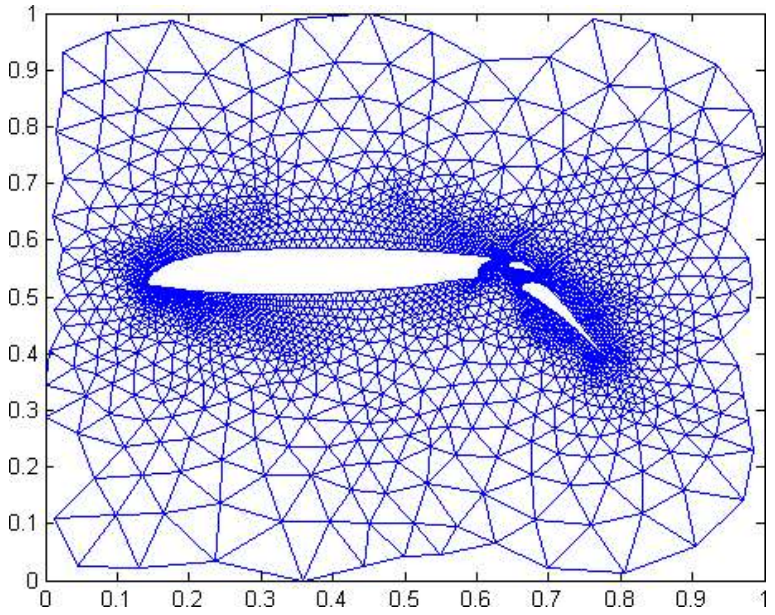
Simulation issues

- Field calculations with finite element programs.
- Some small-scale detectors (e.g. GEMs) contain exposed dielectrics. Charge can accumulate on these leading to dynamic effects.
- Transport, and thus diffusion and gain, of electrons at small scales and in inhomogeneous fields.
- Gain calculations in Penning mixtures.

Issues with field calculations

- Analytic fields are known for many 2D configurations.
- But the devices discussed in this meeting are 3D, frequently containing dielectric materials. Analytic solutions for these devices are very rare.

- A popular way out is to use the finite element method:
  - almost any geometry;
  - dielectrics;
  - commercial software;
  - graphical user interfaces ...



The price to pay for finite elements

- Finite element programs focus on the wrong thing: they solve the potential V, but we do not really need it:
  - quadratic shape functions do a fair job at approximating $V \approx \log(r)$ potentials;
  - potentials are continuous.
- E is what we use, but:
  - gradients of quadratic shape functions are linear and not suitable to approximate our $E \approx 1/r$ fields with, left alone $E \approx 1/r^2$ fields;
  - electric fields are discontinuous;
  - ~50 % accuracy in high-field areas is common.

Food for thought ...

- The Finite Element Method is a very useful tool which can make a good engineer better, but it can make a bad engineer dangerous. [Robert D. Cook, Professor of Mechanical Engineering University of Wisconsin, Madison]

- One should wonder what the Finite Element Method cam do in the hands of a physicist !

Field calculations – way out

- Currently, a plausible way out seems to be the use of the integral equation or boundary element method.
- These methods place charges outside the problem domain and integrate the field using correct 3D expressions: no discontinuities, good approximation of small scale structures.
- But ... such programs are not widely available. One option would be to use a program produced recently by a group in India (Supratik Mukhopadhyay et al.).

Dynamic effects

- One detailed study of dynamic effects that I am aware of was done by Vitali Tikhonov (2002).
- He used an iterative approach:
  - finite element calculation of the GEM field;
  - tracking of electrons to determine surface charges;
  - surface charges added to the finite element model;
  - iteration until convergence achieved.
- Difficulties:
  - surface conductivity not well established;
  - all problems of the finite element approach;
  - laborious.

Issues with transport

- In e.g. argon-based gas mixtures, the mean free path is a few microns – i.e. comparable to the size of elements of the detector.

- Since the field may well vary on the scale of microns, the traditional statistical approach reaches the limits of its applicability.

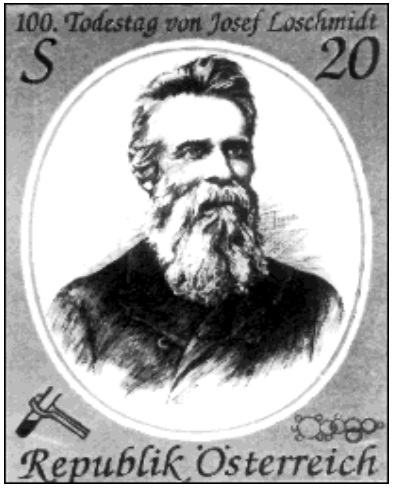
- Instead, a Magboltz-like stepping algorithm with inhomogeneous field needs to be developed.

Amadeo Avogadro
(1776-1856)

Distances in gases

- Number of Ar atoms in a cm³:
  - Avogadro's number: $6.022\ 10^{23}$ atoms/mole ÷
  - Atomic weight of Ar: 40 g/mole ×
  - Density of Ar: $1.782\ 10^{-3}$ g/cm³ =
  - Loschmidt's number: $\mathscr{L} = 2.7\ 10^{19}$ atoms/cm³

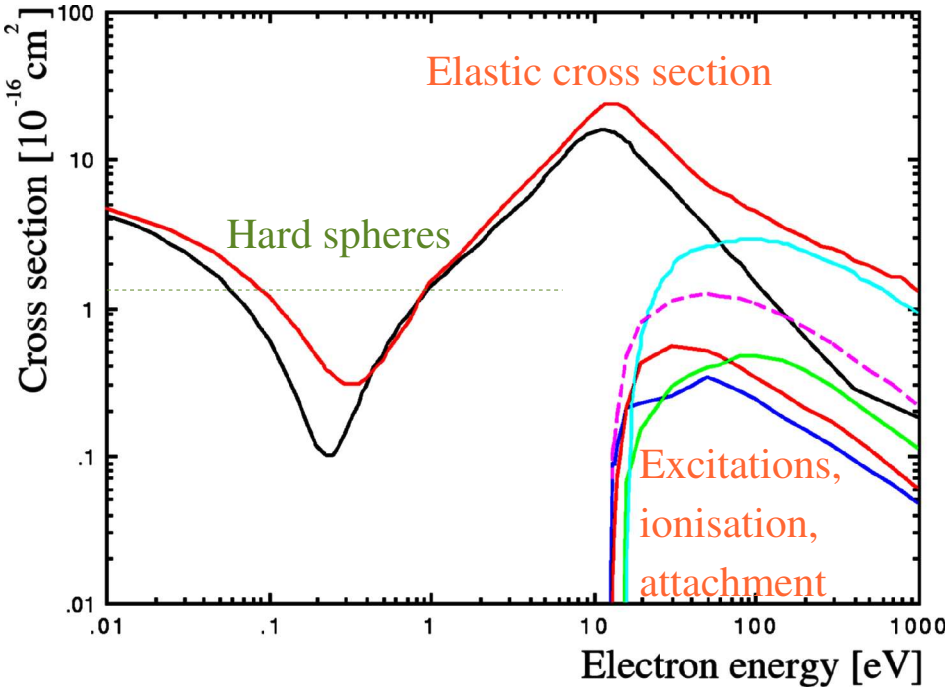
- Distance between neighbouring Ar atoms:
  - $\frac{4}{3}\pi r^3 \times 2.7\,10^{19} = 1$: $d \approx 5$ nm



Josef Loschmidt
(1821-1895)

Cross section of argon

- Cross section in a hard-sphere model:
  - Radius: 70 pm (`http://www.webelements.com`)
  - Surface: $\sigma = \pi (70\,10^{-10}\,\mathrm{cm})^2 \approx 1.5\,10^{-16}\,\mathrm{cm}^2$
- Measured cross sections, as used by Magboltz:



Mean free path in argon

- We know already that:
  - Cross section of 1 atom: $\sigma \approx 2\ 10^{-16}\ \mathrm{cm}^2$
  - Atoms per volume: $\mathscr{L} \approx 2.7\ 10^{19}\ \mathrm{atoms/cm}^3$

- Mean free path for an electron ?
  - An electron hits all atoms of which the centre is less than a cross section radius from its path.
  - Over a distance L, the electron hits $\mathscr{L}\sigma L$ atoms.
  - Hence, the mean free path is $\lambda_e = 1/(\mathscr{L}\sigma) \approx 2\ \mu\mathrm{m}$.
  - Much larger than the distance between atoms, 5 nm !

Scale ≫ mean free path (> 1 mm)

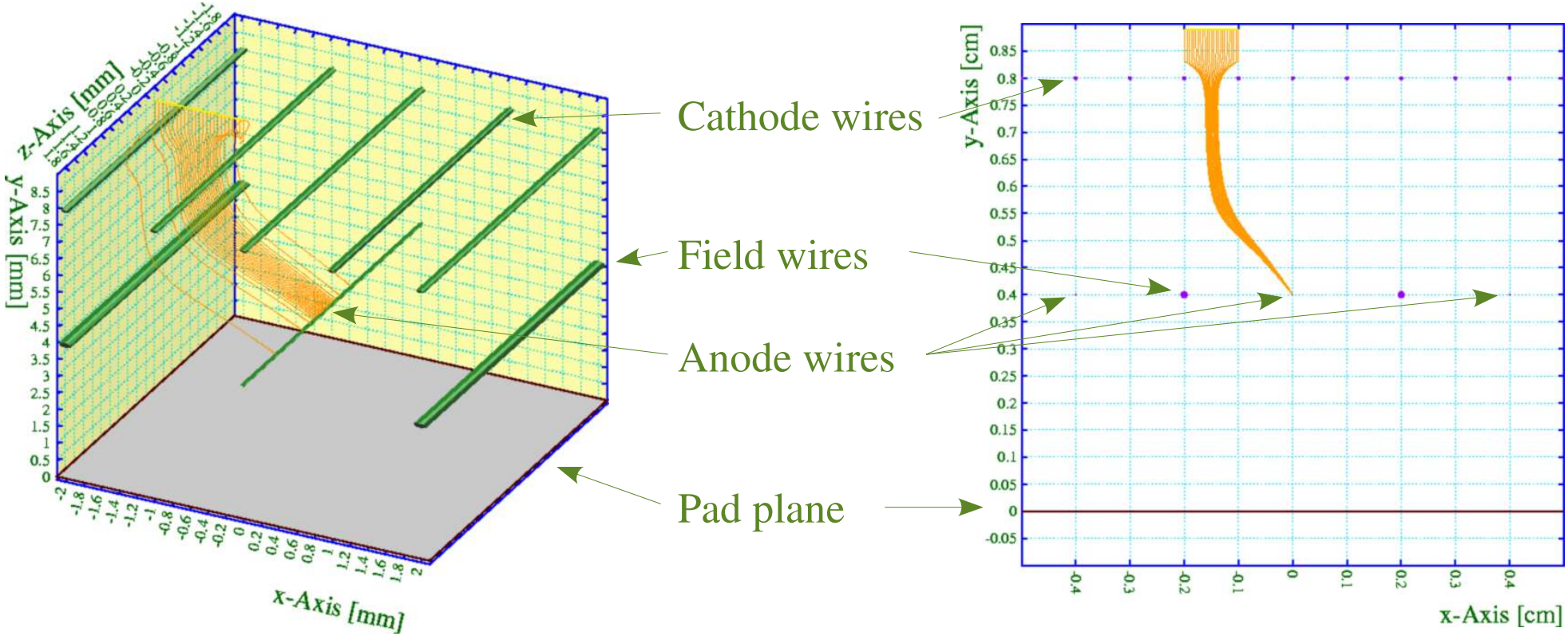
- For practical purposes, electrons from a given starting point reach the same electrode – but with a spread in time and gain.

- Electrons transport is treated by:
  - integrating the equation of motion, using the Runge, Kutta, Fehlberg method, to obtain the path;
  - integrating the diffusion and Townsend coefficients to obtain spread and gain.

- This approach is adequate for TPCs, drift tubes etc.

Analytic integration

- Example: a TPC read-out cell



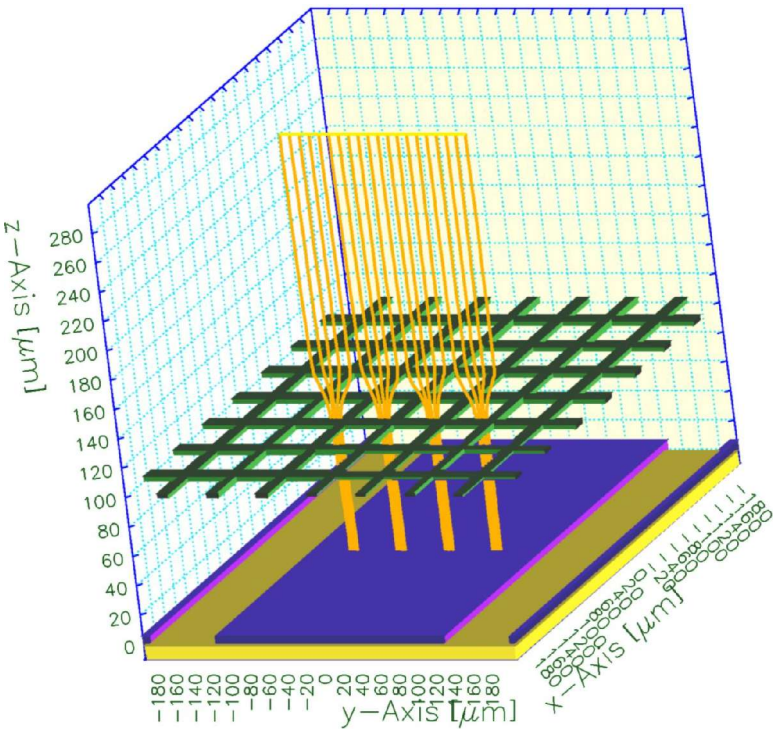
Scale > mean free path (100 μm - 1 mm)

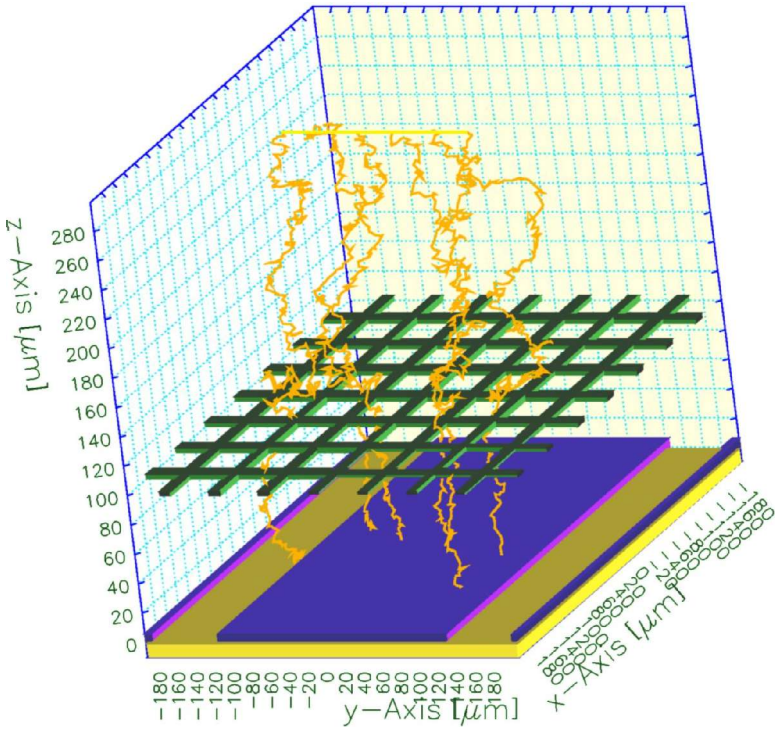
- Electrons from a single starting point may end up on any of several electrodes.
- Calculations use Monte Carlo techniques, based on the mean drift velocity and the diffusion tensor computed by microscopic integration of the equation of motion in a constant field. Gain depends on the path.
- This approach is adequate as long as the drift field is locally constant – a reasonably valid assumption in a Micromegas but less so in a GEM.

Analytic vs Monte Carlo

- Analytic integration
  - Runge-Kutta-Fehlberg technique;
  - automatically adjusted step size;
  - optional integration of diffusion, multiplication and losses.

- Monte Carlo integration
  - non-Gaussian in accelerating, divergent and convergent fields;
  - step size to be set by user.

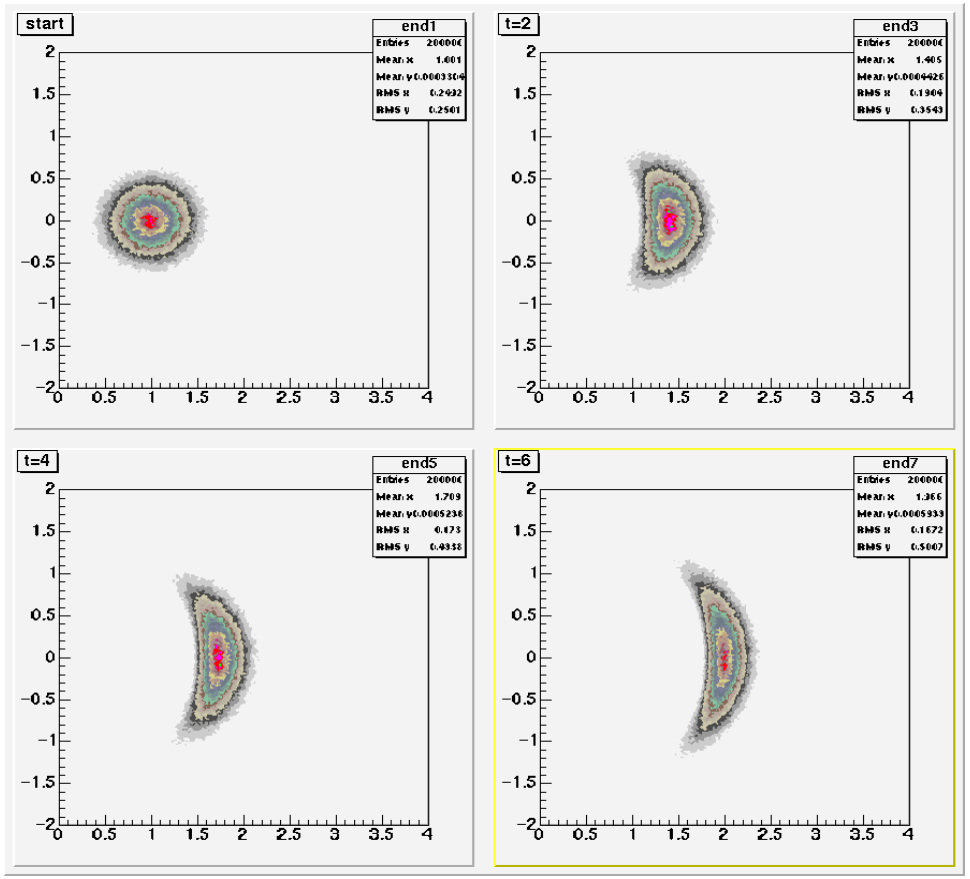




[Figures made by Gilles Barouch, CEA]

Diffusion

- Diffusion is not necessarily a Gaussian process, as illustrated here for a radial flow at constant mobility: $\dot{x} = \mu E_x$, $\dot{y} = \mu E_y$
- Virtually harmless for converging flow, e.g. on approach of anode wires.
- Makes Gaussian formulae inadequate for diverging flow as found in GEMs.



[In collaboration with Gabriele Croci]

Scale ~ mean free path (1-100 μm)

- Field variations during the free flight between collisions, affect the path – which may therefore no longer be parabolic.

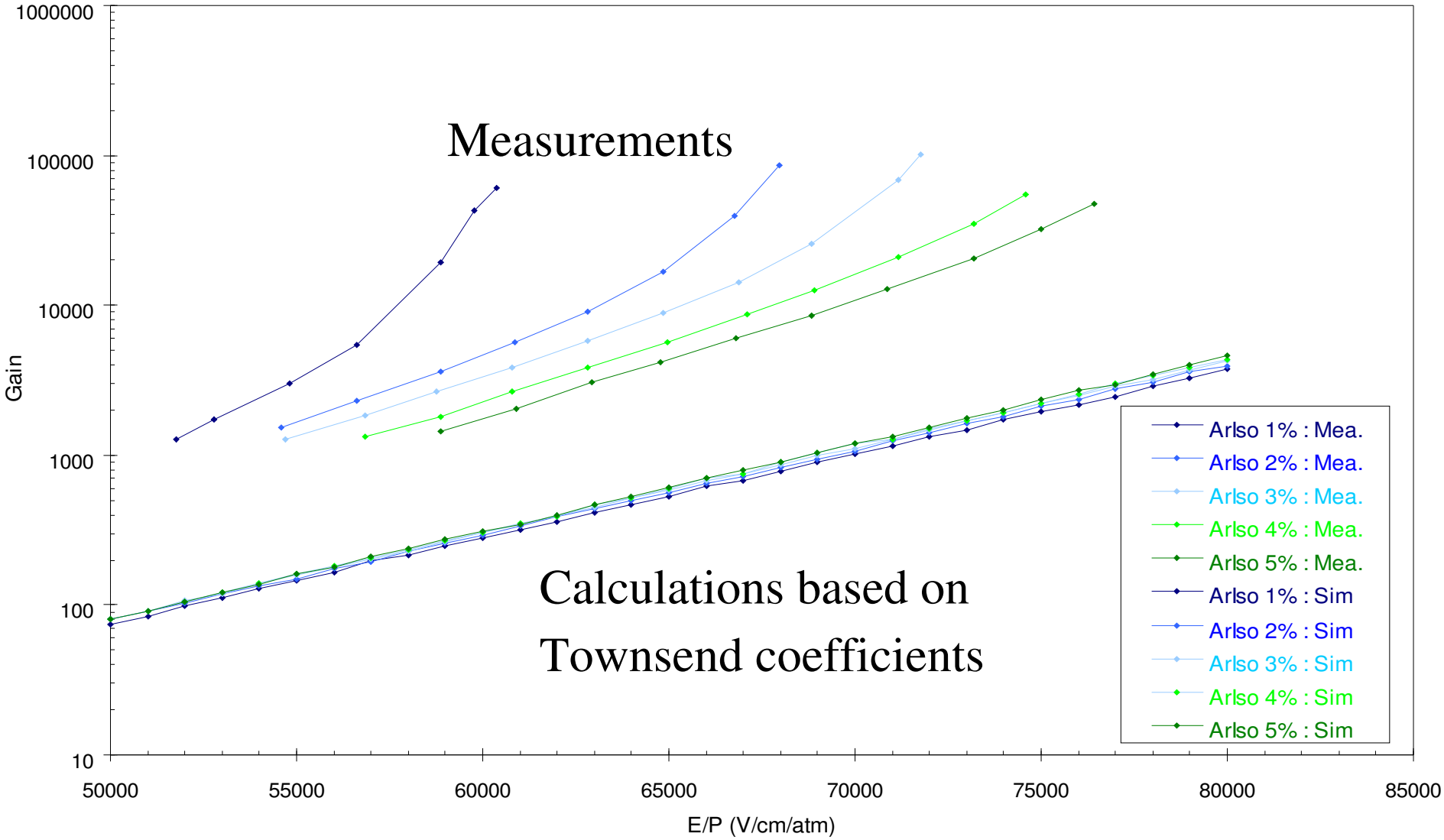
- The only viable approach here seems to be a complete microscopic simulation of the transport processes, taking local field variations into account.

- This method, still to be written, should be based on the Magboltz program.

Issues regarding the gain

- Townsend coefficients as such are computed with fair accuracy by Magboltz.
- But in several gas mixtures, the gain is (grossly) underestimated if one integrates the Townsend coefficient as computed by Magboltz.
- The discrepancy is often due to the Penning effect: excited states of gas A ionise molecules of gas B. Excitation rates nearly always exceed ionisation rates and the effect, when allowed, has a major impact.

Gain in Ar – iC_4H_{10} (1-5%)



[Plot: David Attié, CEA Saclay]

Details of the Magboltz output

- Example: 5 % iC_4H_{10} at E = 60 kV/cm
- Isobutane:
  - Excitations:
    - 7.4 eV: 19 GHz
    - 9.7 eV: 5 GHz
    - 17.0 eV: 0.4 GHz
  - Ionisation:
    - 10.67 eV: 9 GHz
- Argon:
  - Excitations:
    - 11.55 eV (S): 12 GHz
    - 13.0 eV (P): 12 GHz
    - 14.0 eV (D): 4 GHz
  - Ionisation:
    - 15.7 eV: 12 GHz
- If all excited Ar atoms ionise iC_4H_{10}, the ionisation rate goes from 21 GHz to 49 GHz, more than doubling the Townsend coefficient.

Penning transfer rate

- Comparing at 60 kV/cm:
  - Measured: gain ~ 1800, α ~ 1500/cm
  - Calculated: gain ~ 300, α ~ 1140/cm
  - (Magboltz: α ~ 1150/cm)

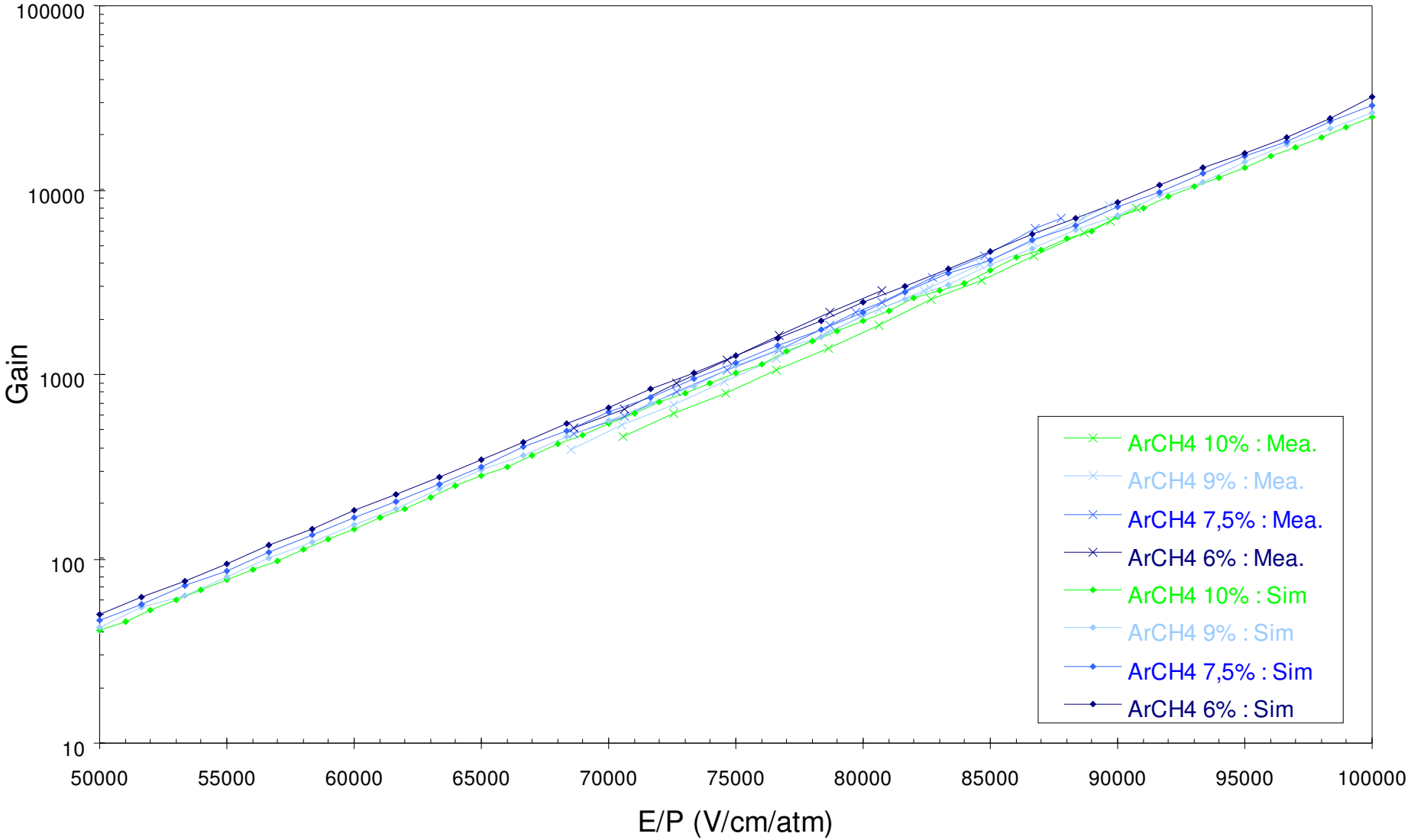
- This translates to a 25 % Penning transfer rate, in line with commonly quoted figures for such mixtures.

- At present, there are few solid theoretical predictions of the Penning transfer rate.

$Ar\text{-}CH_4$

- Methane:
  - Excitations:
    - 9.0 eV (dissociation)
    - 10.0 eV (idem)
    - 11.0 eV (idem)
    - 11.8 eV (idem)
  - Ionisation:
    - 12.99 eV
- Argon:
  - Excitations:
    - 11.55 eV (S)
    - 13.0 eV (P)
    - 14.0 eV (D)
  - Ionisation:
    - 15.7 eV
- Only the, relatively infrequent, argon-D excitation can lead to a Penning effect.

Gain in Ar – CH_4 (6-10%)



[Plot: David Attié, CEA Saclay]

Penning transfers in the Alice TPC

- In 90 % Ne + 10 % CO_2, apparently 40 % of the Ne^* ionise CO_2, enhancing the gain by a factor 2-5 !

Transfers:

$Ne^* \rightarrow CO_2^+$:

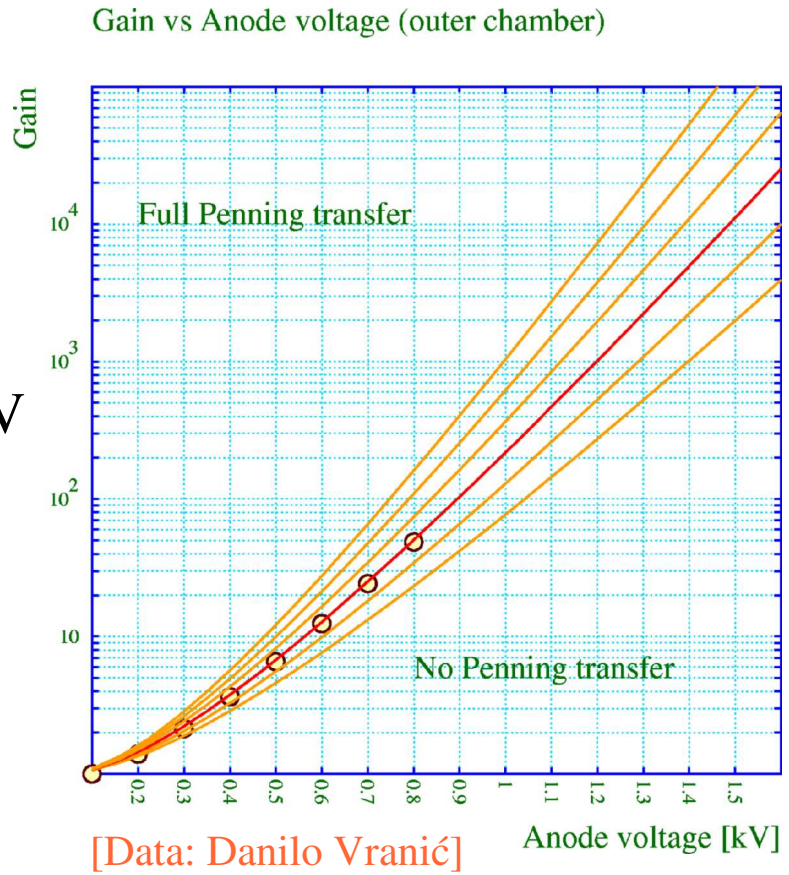
Ne^*: 16.615 eV

CO_2^+: 13.769 eV

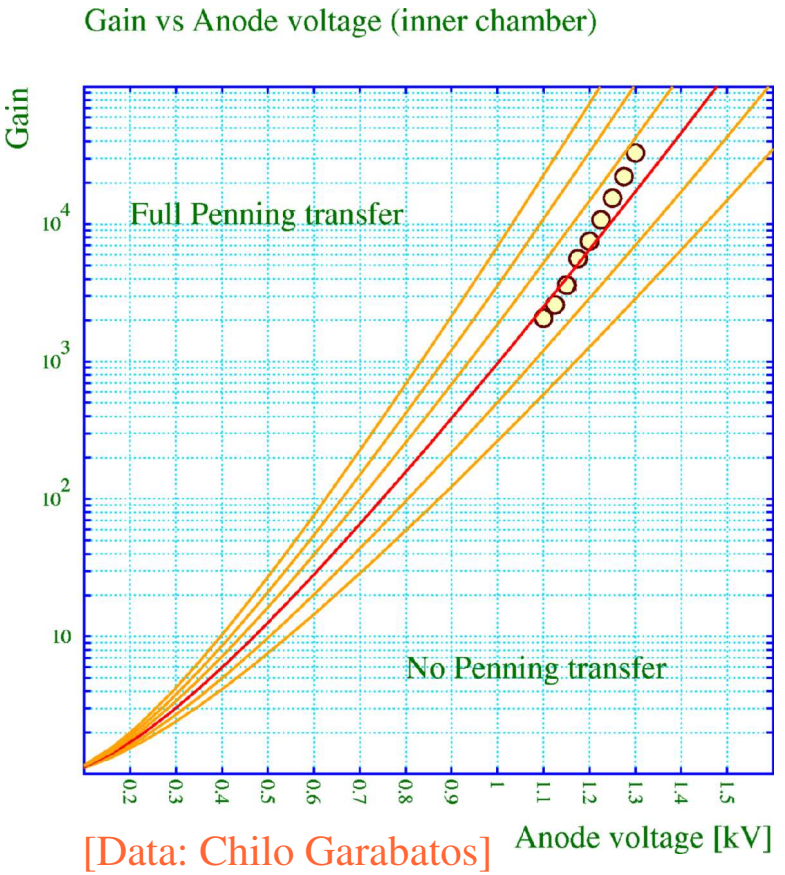
$CO_2^* \rightarrow Ne^+$:

CO_2^*: < 15 eV

Ne^+: 21.56 eV



[Data: Danilo Vranić]



[Data: Chilo Garabatos]

Gain – approach

- Magboltz produces tables of excitation rates as part of its output.

- Pending theoretical estimates of the Penning transfer rates, the transfer rate will have to be obtained from measurements.

Conclusion

- It is reasonably clear how the current difficulties with simulations should be addressed.
- Work in some areas, e.g. transport at the 100 μm scale and simplification of the use of Penning transfers rates, is in progress.
- In other domains, e.g. transport at the 10 μm scale and boundary element methods, needs to be started.

Backup slides

Penning effect at 80 kV/cm

- Example: 5 % iC_4H_{10} at E = 80 kV/cm
- isobutane:
  - Excitations:
    - 7.4 eV: 22 GHz
    - 9.7 eV: 7 GHz
    - 17.0 eV: 0.9 GHz
  - Ionisation:
    - 10.67 eV: 14 GHz
- argon:
  - Excitations:
    - 11.55 eV (S): 17 GHz
    - 13.0 eV (P): 21 GHz
    - 14.0 eV (D): 7 GHz
  - Ionisation:
    - 15.7 eV: 26 GHz
- If all excited Ar atoms ionise iC_4H_{10}, the ionisation rate goes from 40 GHz to 85 GHz, more than doubling the Townsend coefficient !