EDIT 2011

Excellence in Detectors and Instrumentation Technologies
CERN, Geneva, Switzerland - 31 January - 10 February 2011

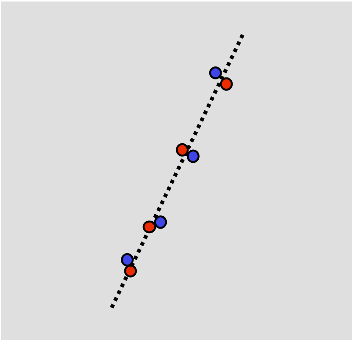
GASEOUS DETECTORS FUNDAMENTS

Fabio Sauli
TERA Foundation and CERN

MAIN PARAMETERS:

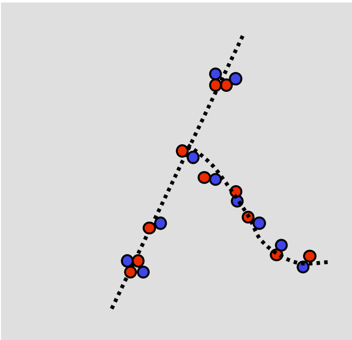
Gas	Density, mg cm^{-3}	E_x eV	E_I eV	W_I eV	$dE/dx\|_{min}$ keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
Ne	0.839	16.7	21.6	30	1.45	13	50
Ar	1.66	11.6	15.7	25	2.53	25	106
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	37	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
iC_4H_{10}	2.49	6.5	10.6	26	5.67	90	220
CO_2	1.84	7.0	13.8	34	3.35	35	100
CF_4	3.78	10.0	16.0	54	6.38	63	120

PRIMARY IONIZATION:



REVIEW OF PARTICLE PROPERTIES ***http://pdg.lbl.gov/***

TOTAL IONIZATION:



Minimum ionizing particles in Argon NTP:

dE/dx: 2.5 keV/cm n_P: 25 ion pairs/cm

Detection efficiency: $\varepsilon = 1 - P_0^n = 1 - e^{-n}$

Thickness:

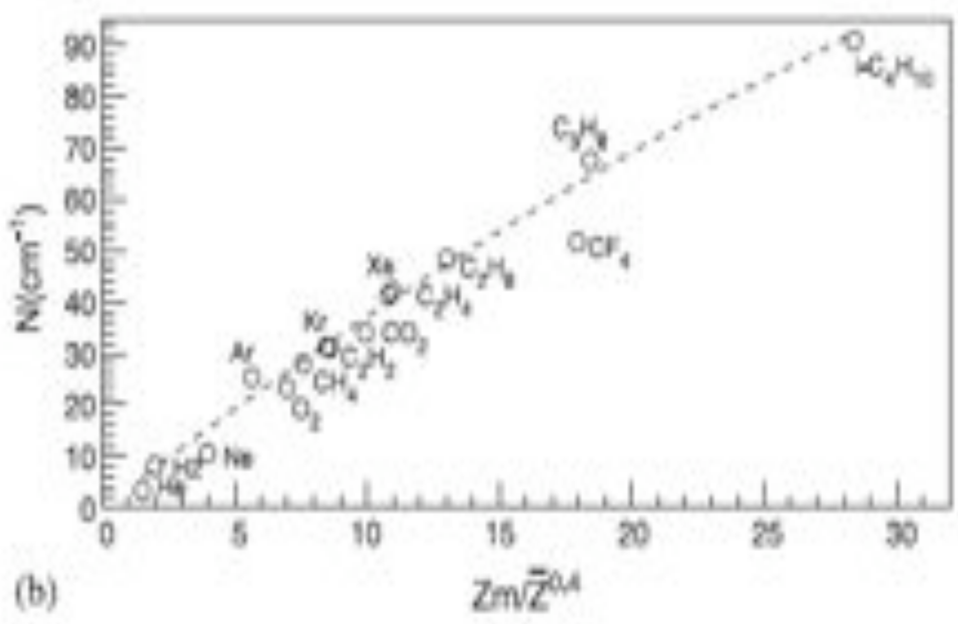
s (mm)	ε (%)
1	91.8
2	99.3

Total number of ion pairs: $n_T = \dfrac{\Delta E}{W_i}$

ΔE = 2.5 keV/cm w_i = 25 eV $n_T \approx$ 100 ip/cm

$$\boxed{\frac{n_T}{n_P} \approx 4}$$

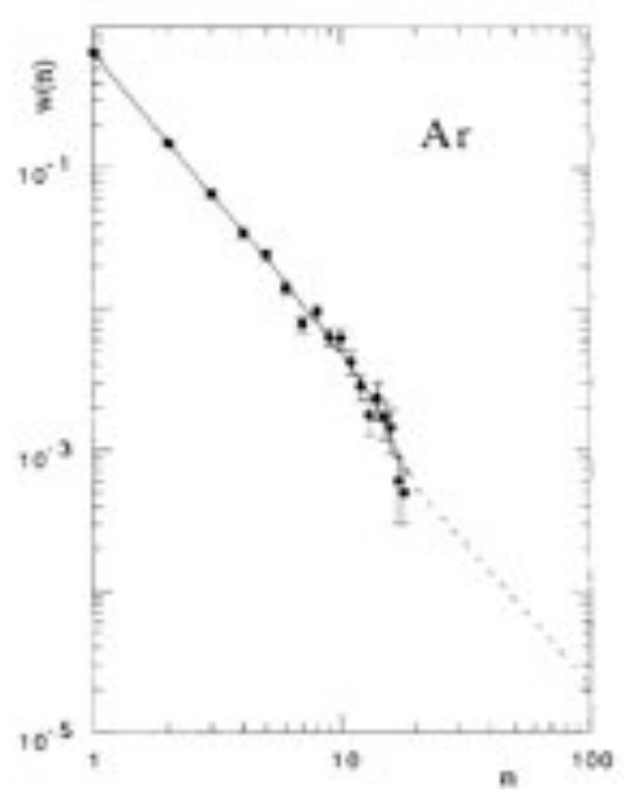
PROGRAM HEED:
NUMBER OF PRIMARY INTERACTIONS (CLUSTERS) IN GASES AT STP



I. B. Smirnov, Nucl. Instr. and Meth. A554(2005)474

http://consult.cern.ch/writeup/heed/

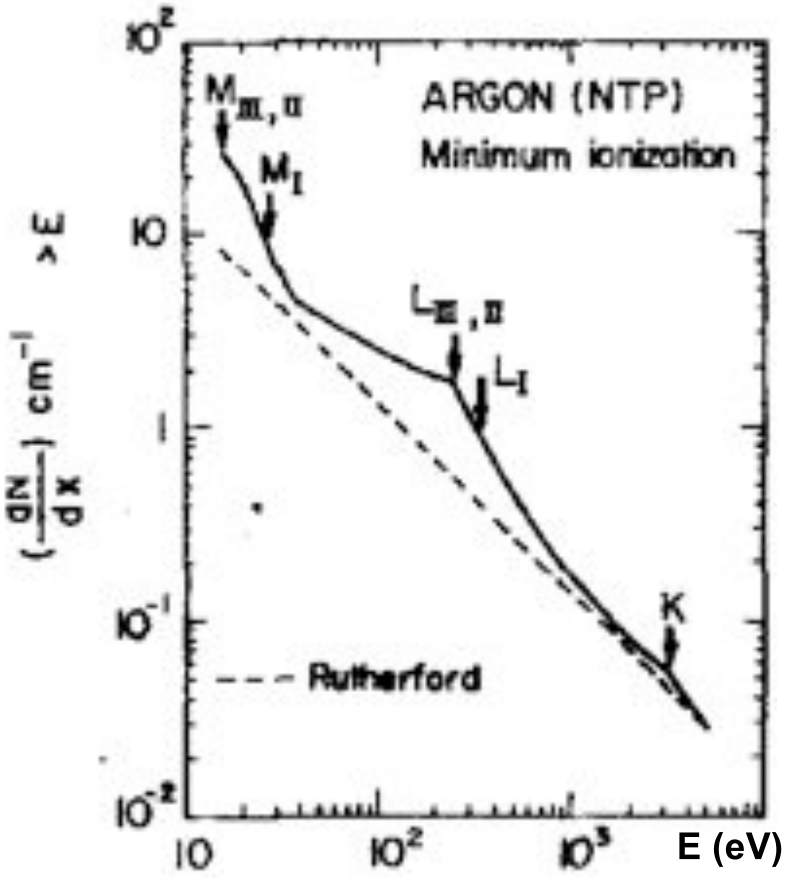
EXPERIMENTAL CLUSTER SIZE PROBABILITY:



H. Fischle et al, Nucl. Instr. and Meth. A301 (1991) 202

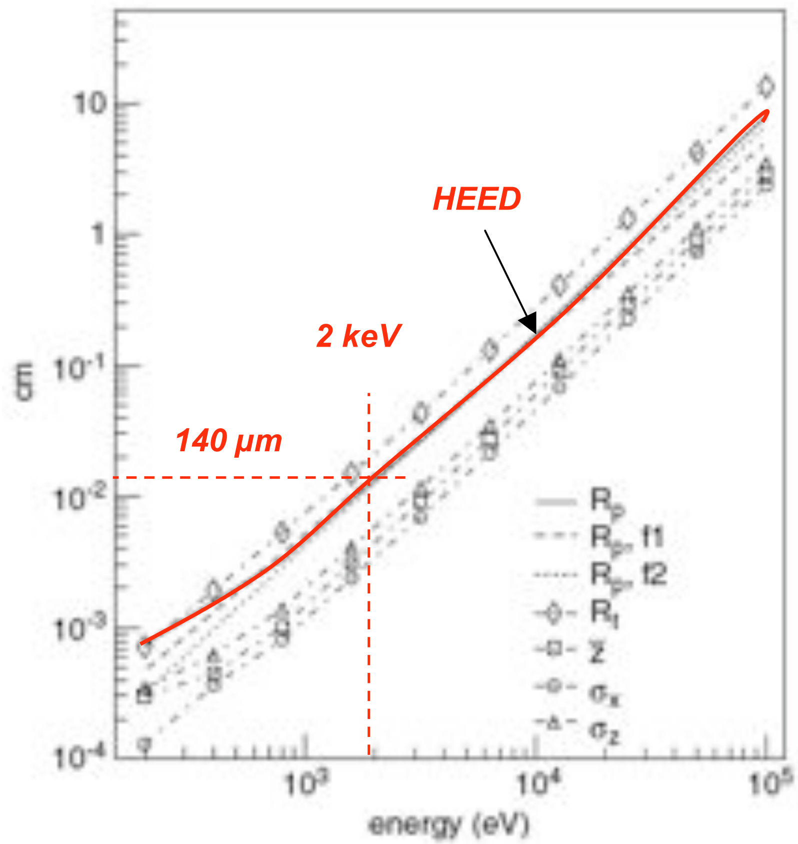
PROBABILITY AND RANGE OF DELTA ELECTRONS

PROBABILITY FOR AN ELECTRON OF ENERGY > E:



F. Lapique and F. Piuz,
Nucl. instr. and Meth. 175(1980)297

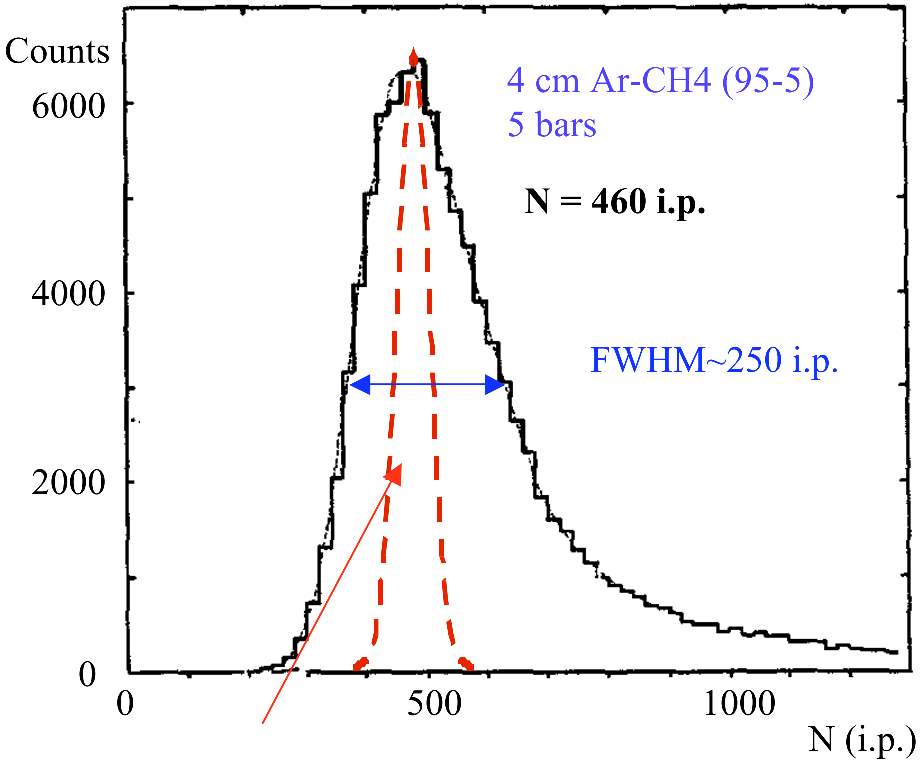
ELECTRON RANGE IN ARGON STP:



I. B. Smirnov,
Nucl. Instr. and Meth. A554(2005)474

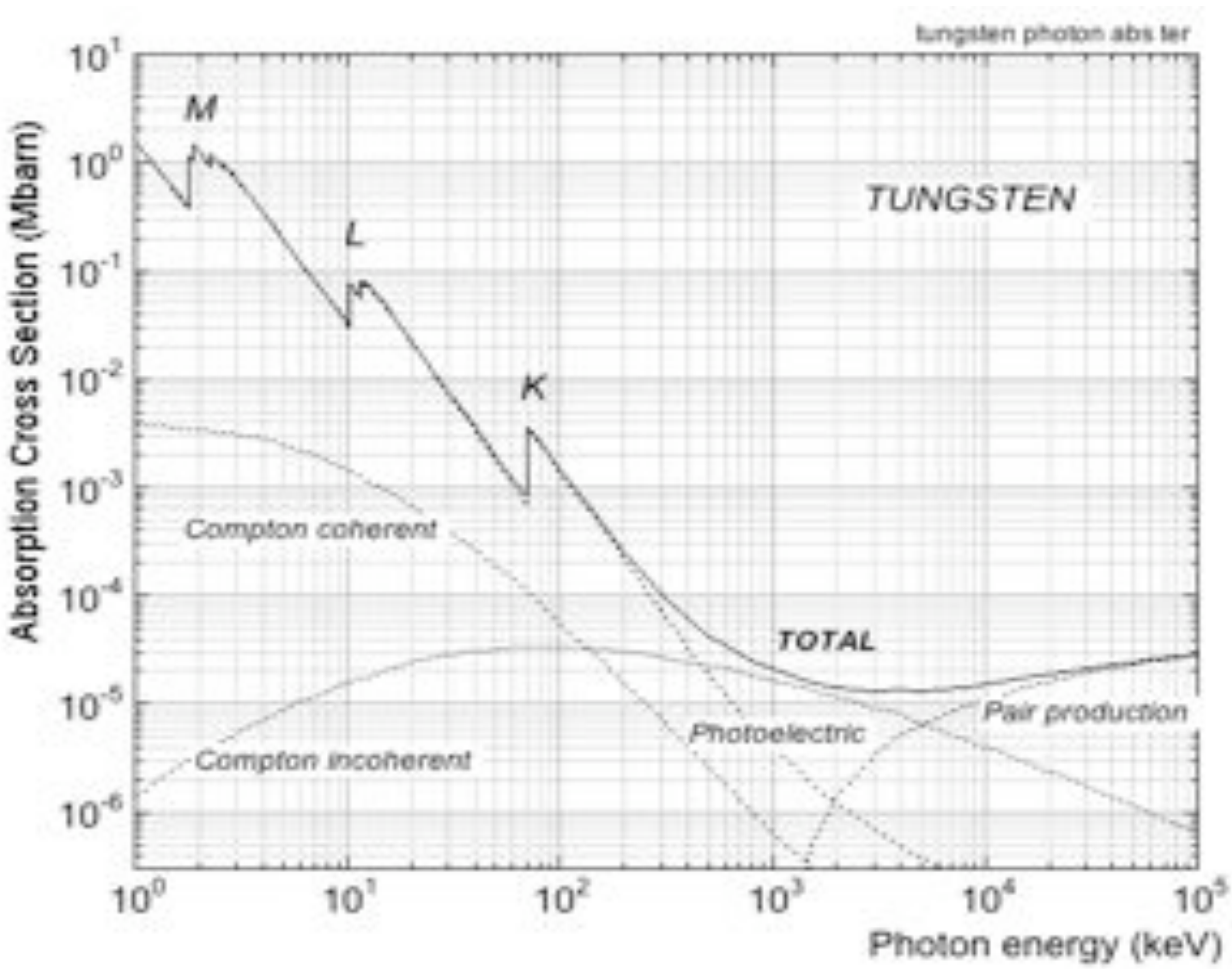
CONSEQUENCED OF DELTA ELECTRONS

LANDAU DISTRIBUTION OF ENERGY LOSS:
POOR RESOLUTION



For a Gaussian distribution:

$\sigma_N \sim 21$ i.p. FWHM ~ 50 i.p.

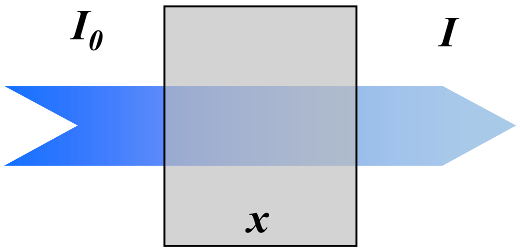


http://xdb.lbl.gov/

http://henke.lbl.gov/optical_constants/

http://physics.nist.gov/PhysRefData/FFast/html/form.html

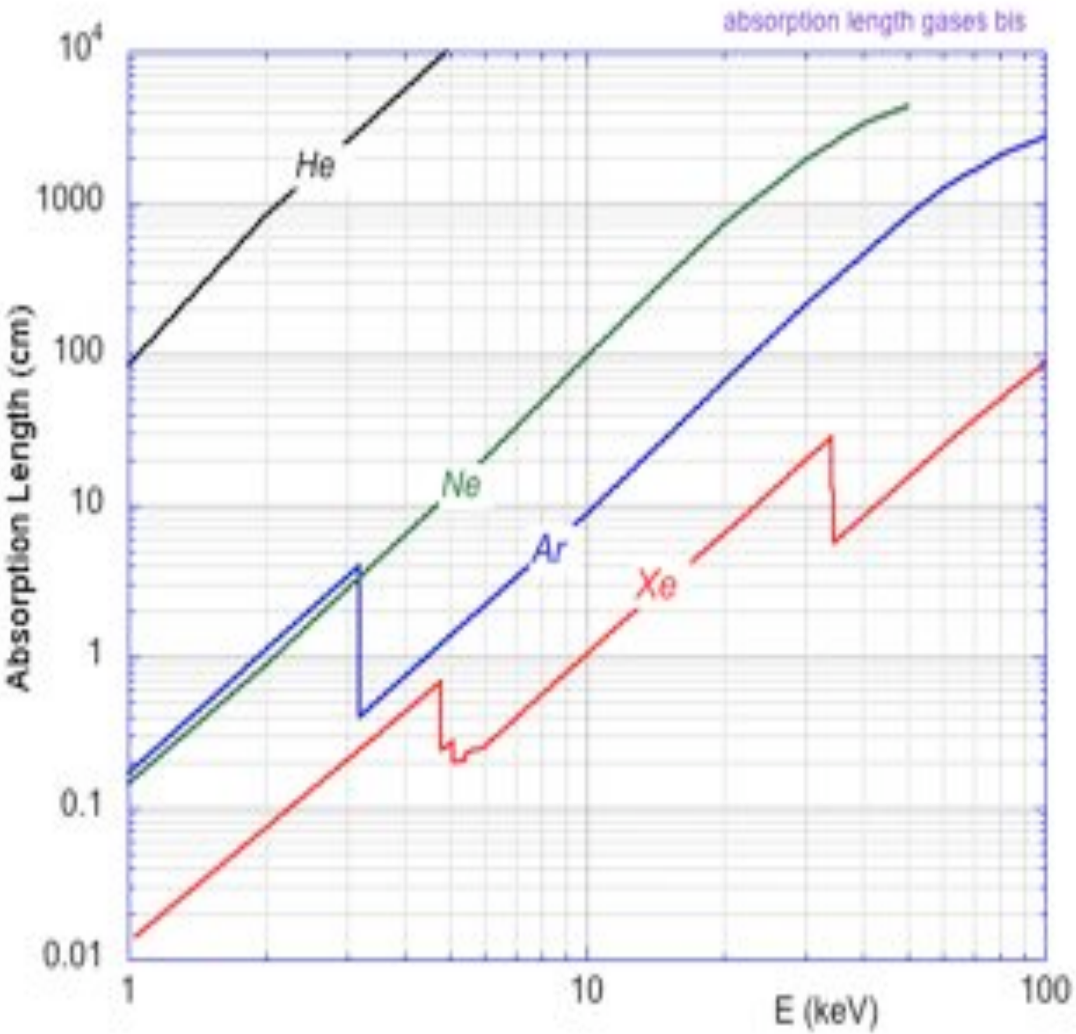
PHOTON ABSORPTION



$$I = I_0 e^{-\frac{x}{l}}$$

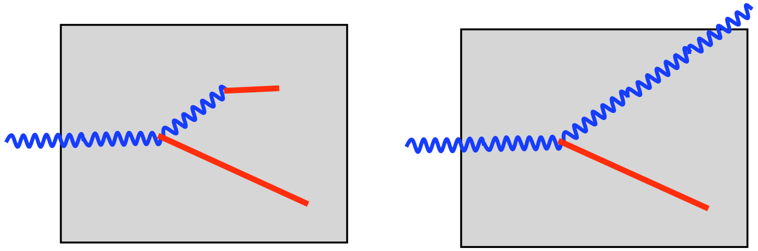
l : absorption length

ABSORPTION LENGTH (STP) VS PHOTON ENERGY

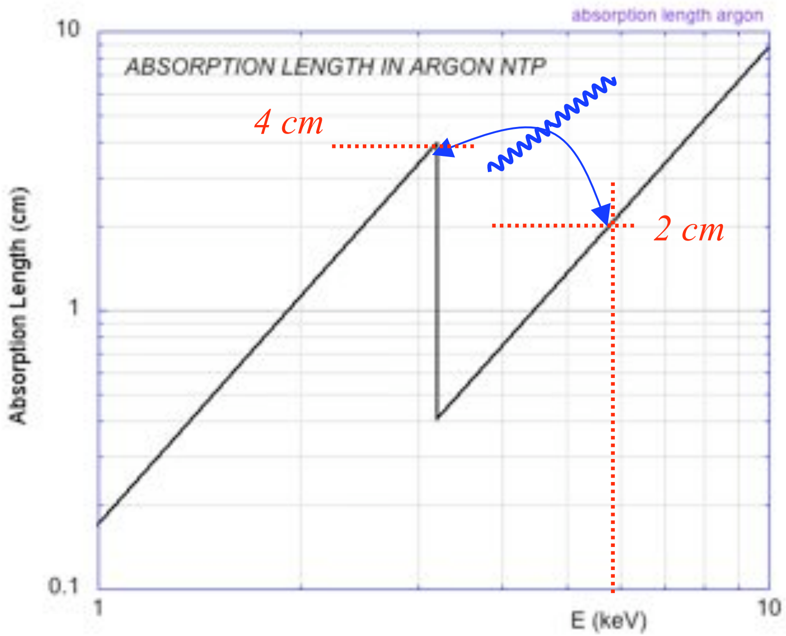


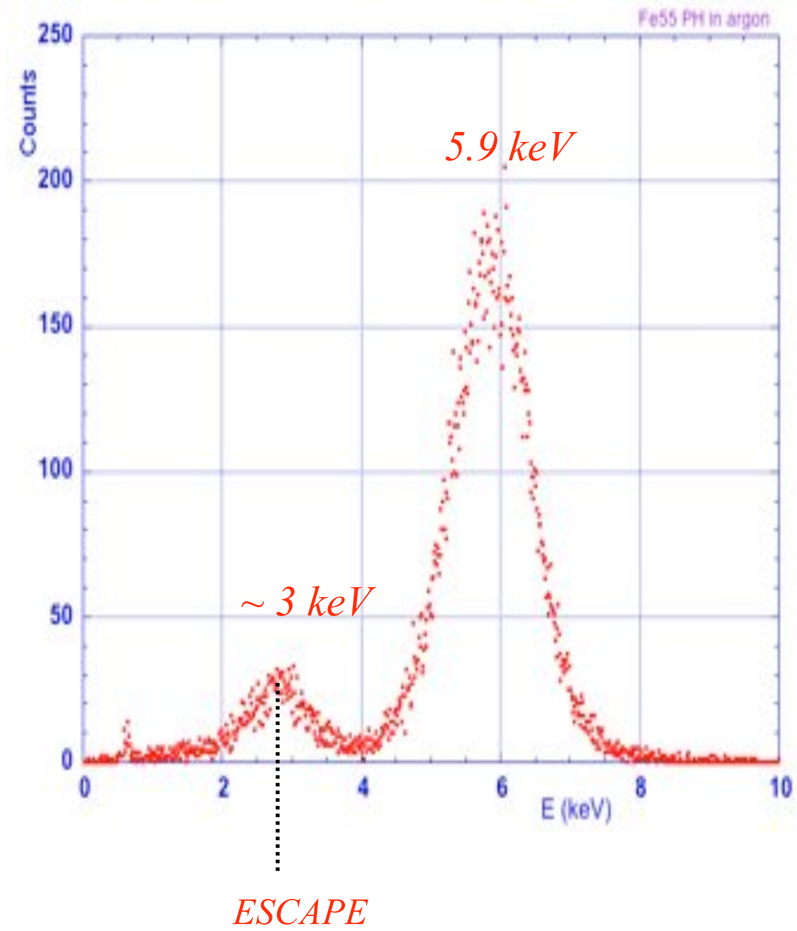
SOFT X-RAYS: FLUORESCENCE YIELD

Fluorescence photons can convert far from the primary interaction, or escape from the sensitive volume (escape peak):

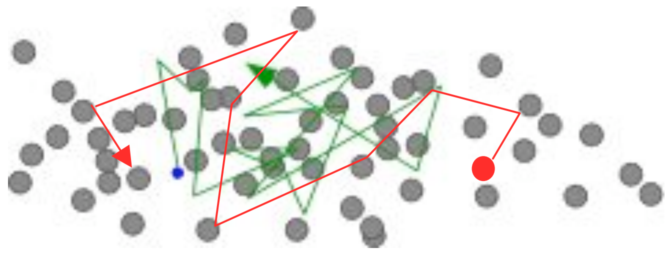


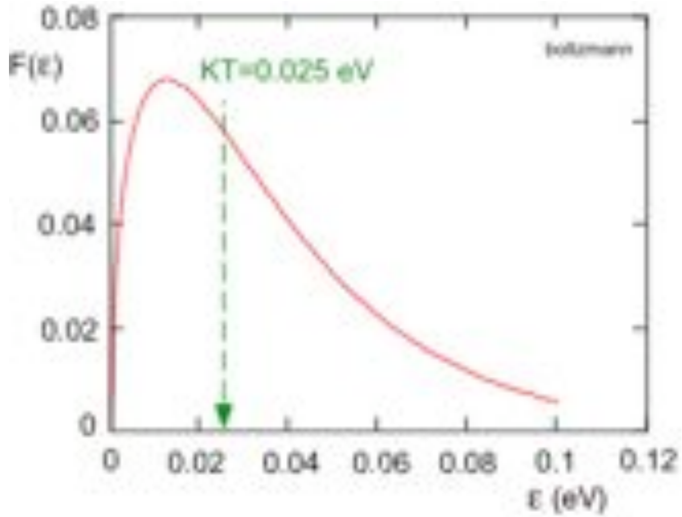
X-RAY ABSORPTION SPECTRUM
^{55}Fe X-Rays (5.9 keV) in Argon:





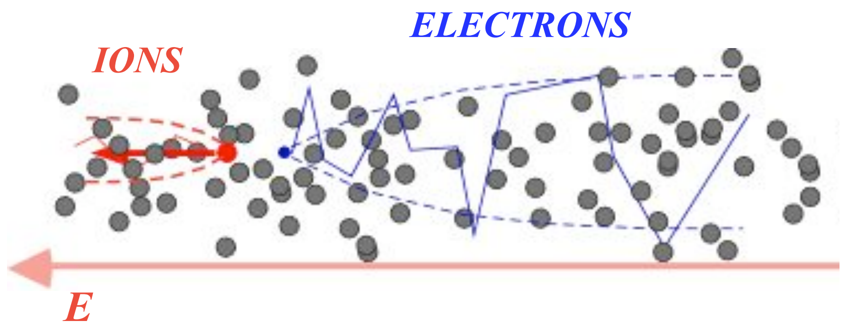
E = 0 : THERMAL DIFFUSION (Ions and electrons):

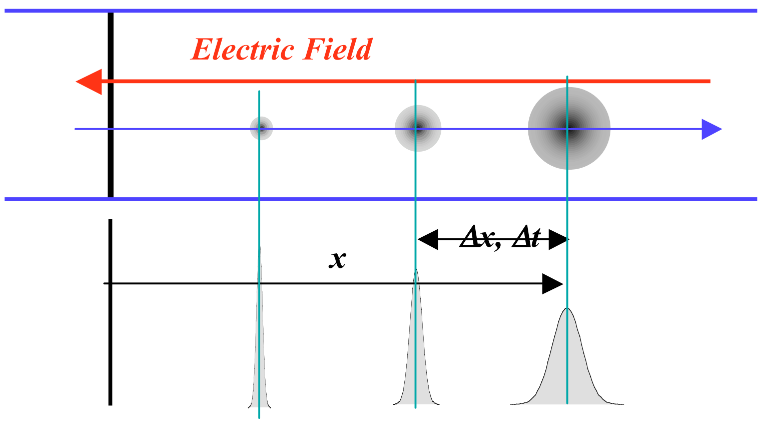




Maxwell energy distribution: $F(\varepsilon) = C\sqrt{\varepsilon}\, e^{-\frac{\varepsilon}{KT}}$

E > 0: CHARGE TRANSPORT AND DIFFUSION



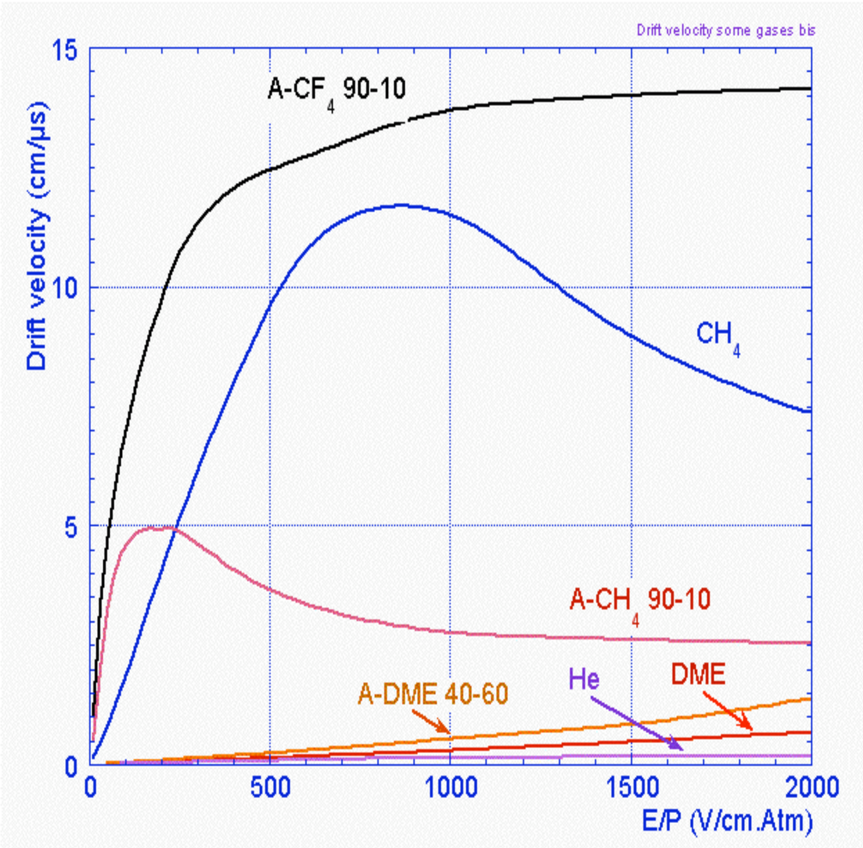


Drift velocity: $w = \frac{\Delta x}{\Delta t}$

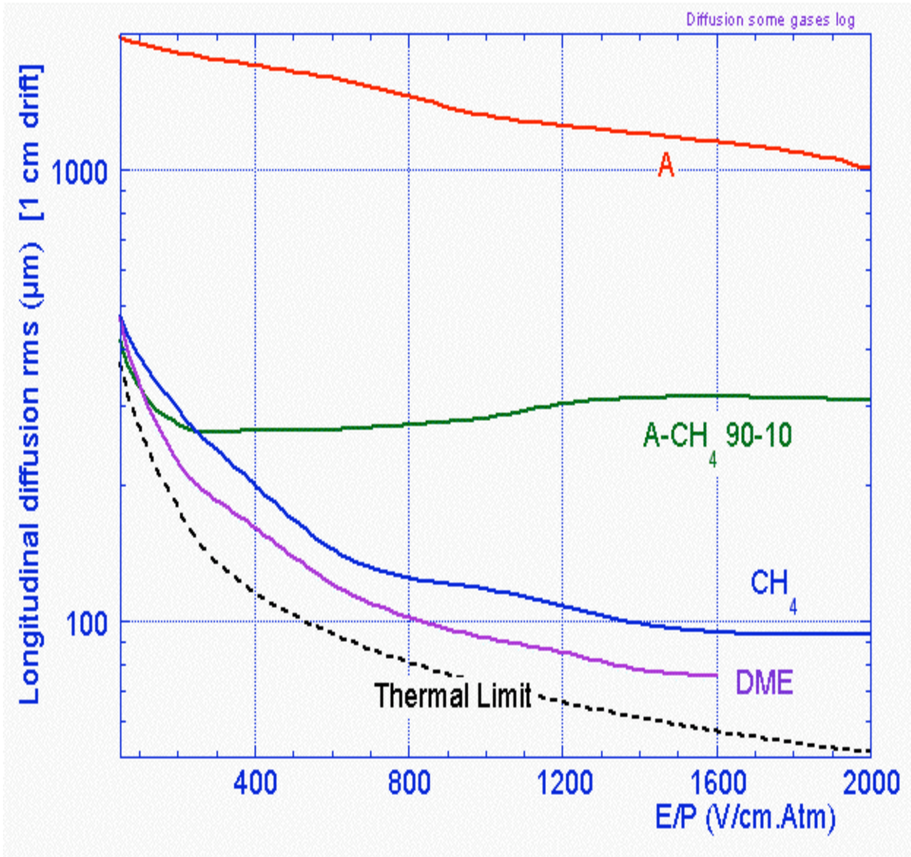
Diffusion: $\sigma = \sqrt{2Dt} = \sqrt{2D\frac{x}{w}}$

ELECTRONS DRIFT VELOCITY

DRIFT VELOCITY:



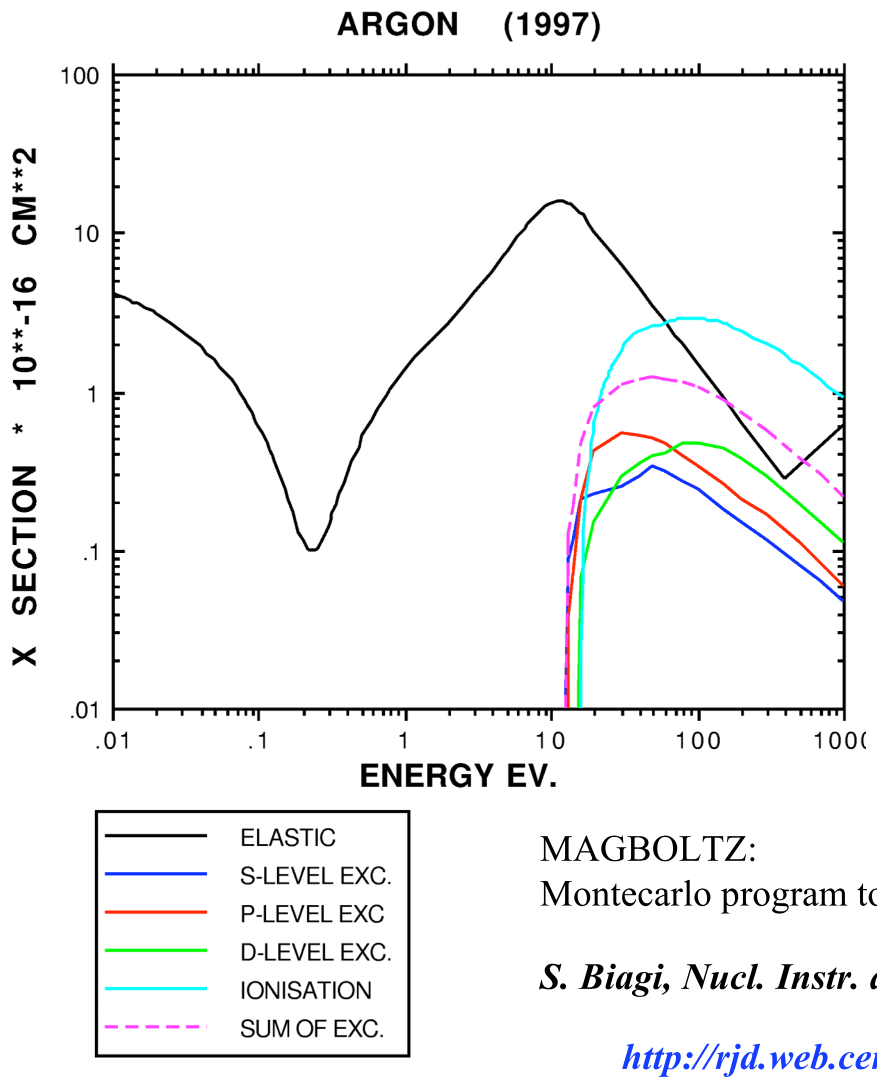
DIFFUSION:

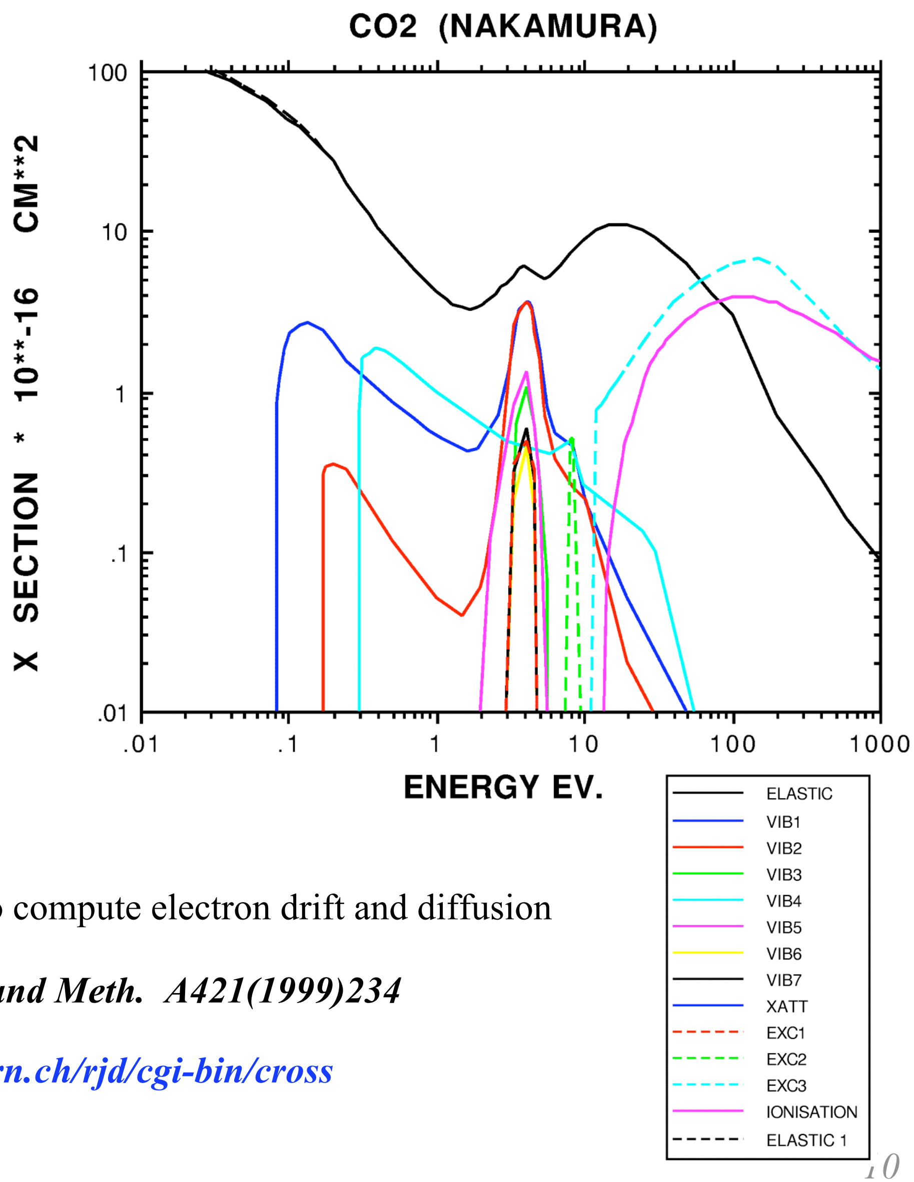


A. Peisert and F. Sauli, drift and Diffusion of Electrons in Gases: a compilation CERN 84-08 (1984)

ELECTRON-MOLECULE CROSS SECTION

Charge transport processes are determined by the various electron-molecule cross sections:





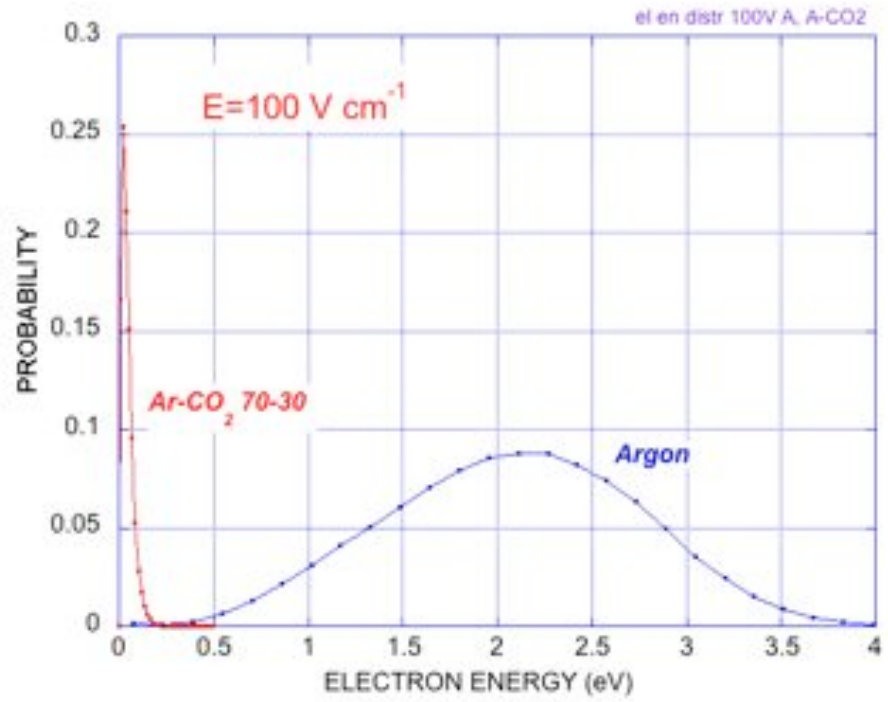
MAGBOLTZ:
Montecarlo program to compute electron drift and diffusion

S. Biagi, Nucl. Instr. and Meth. A421(1999)234

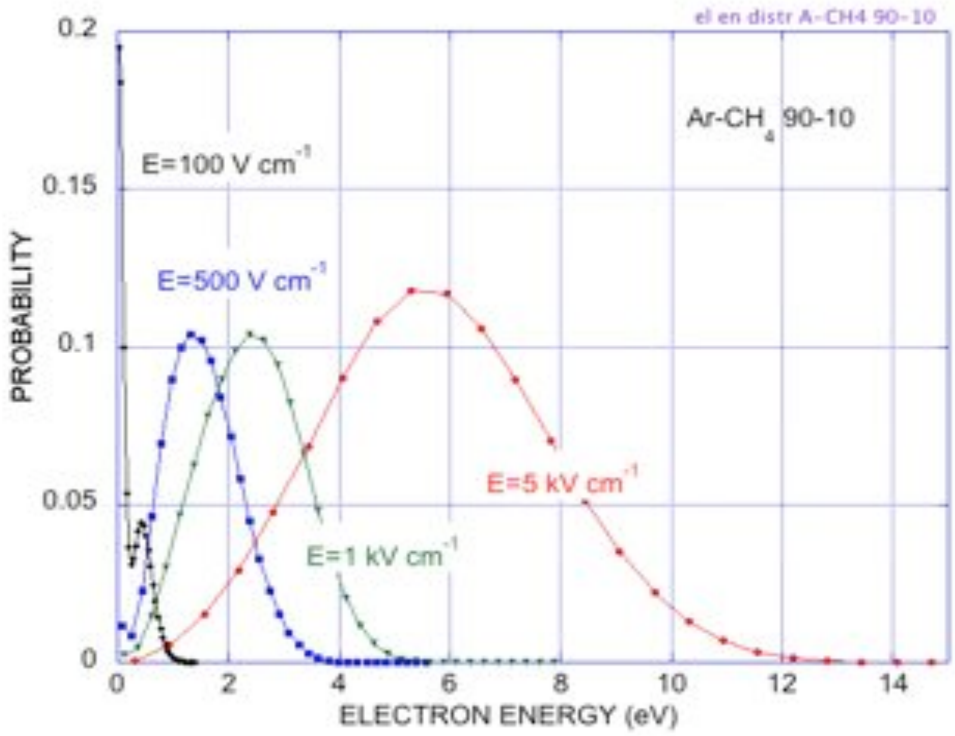
http://rjd.web.cern.ch/rjd/cgi-bin/cross

ENERGY DISTRIBUTION AT INCREASING FIELDS:

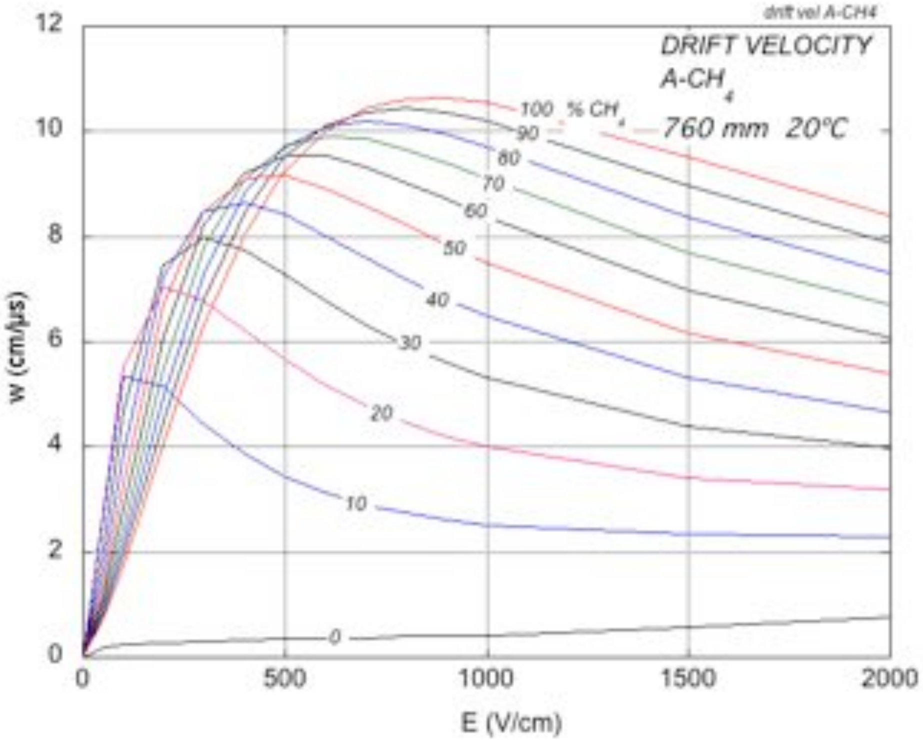
EQUAL FIELD, DIFFERENT GAS:

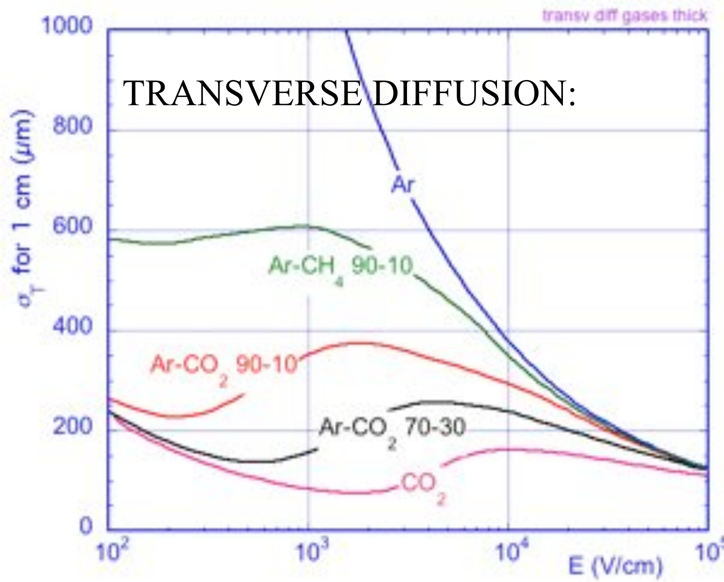


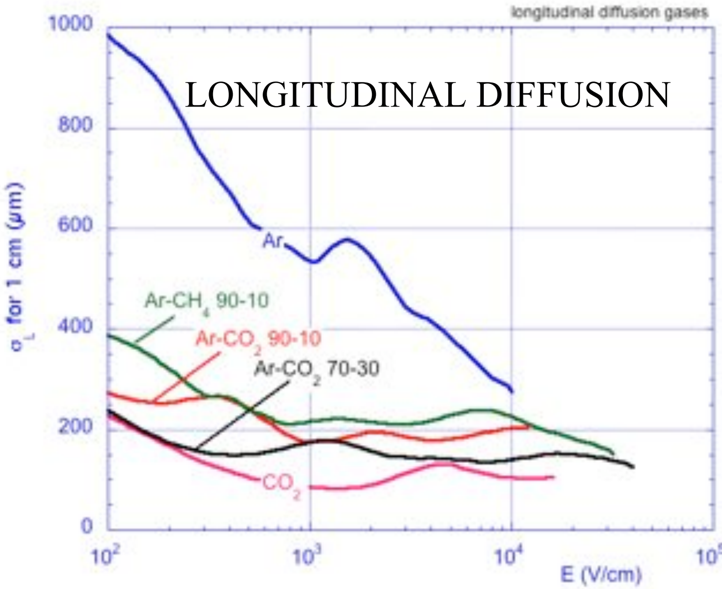
SAME GAS, INCREASING FIELD:



DRIFT VELOCITY IN ARGON-METHANE MIXTURES







EXAMPLE: $Ar\text{-}CH_4$ 90-10) , STP, $E=1 kVcm^{-1}$

$w^- = 2.5$ cm μs^{-1}

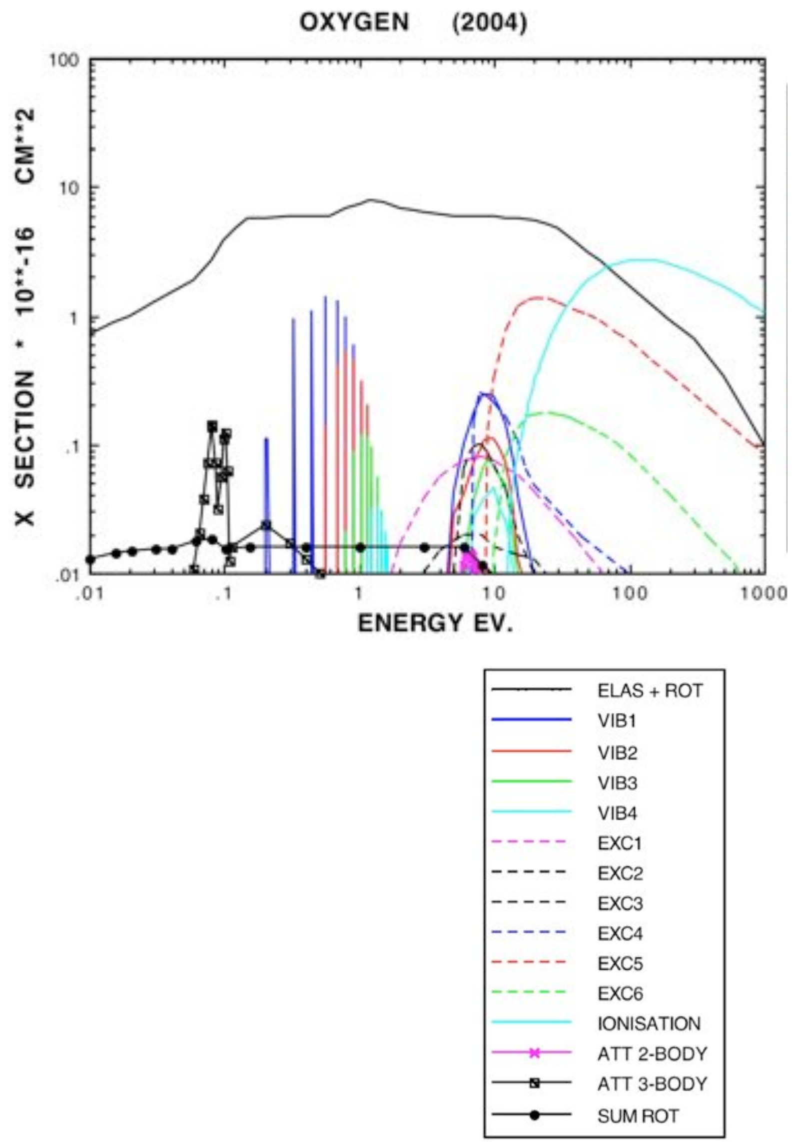
$\sigma_T = 600\ \mu m$

$\sigma_L = 200\ \mu m$

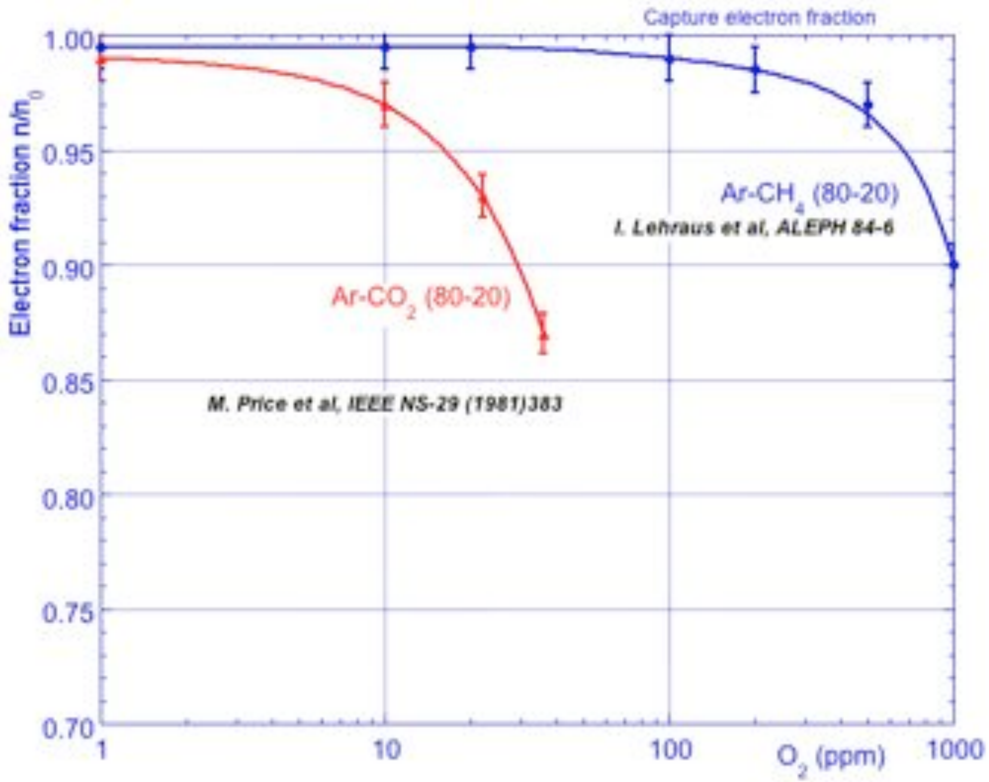
$$\frac{w^-}{w^+} \cong 10^3$$

Computed with MAGBOLTZ

ATTACHMENT CROSS SECTION OF OXYGEN:

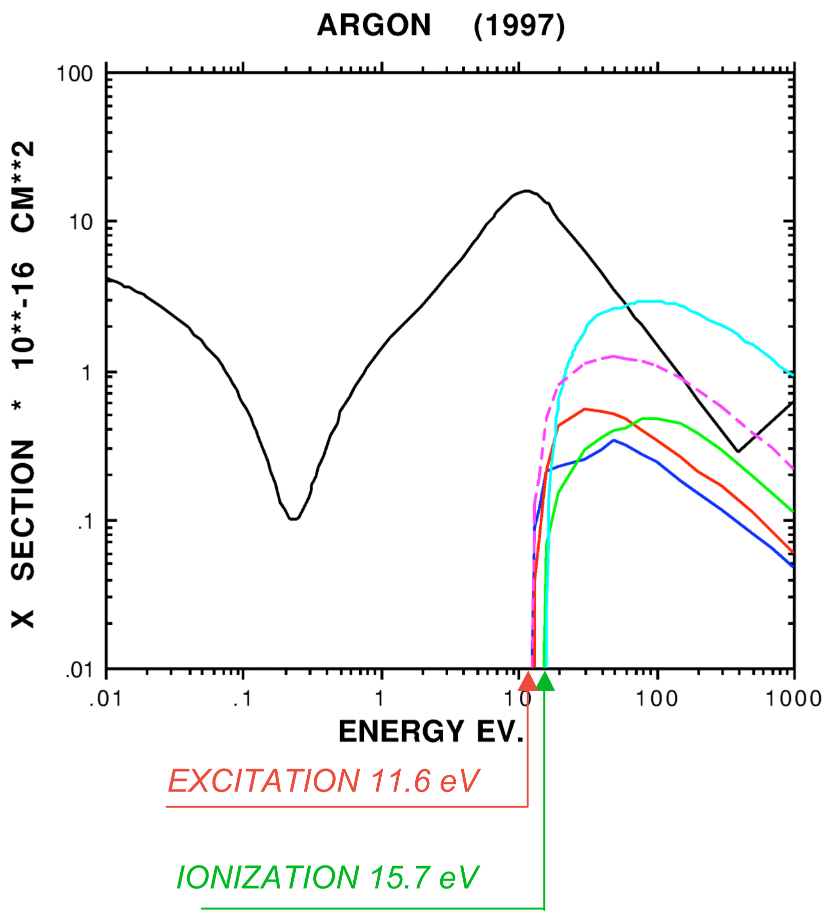


ELECTRONS SURVIVING AFTER 20 CM DRIFT (E = 200 V/cm):

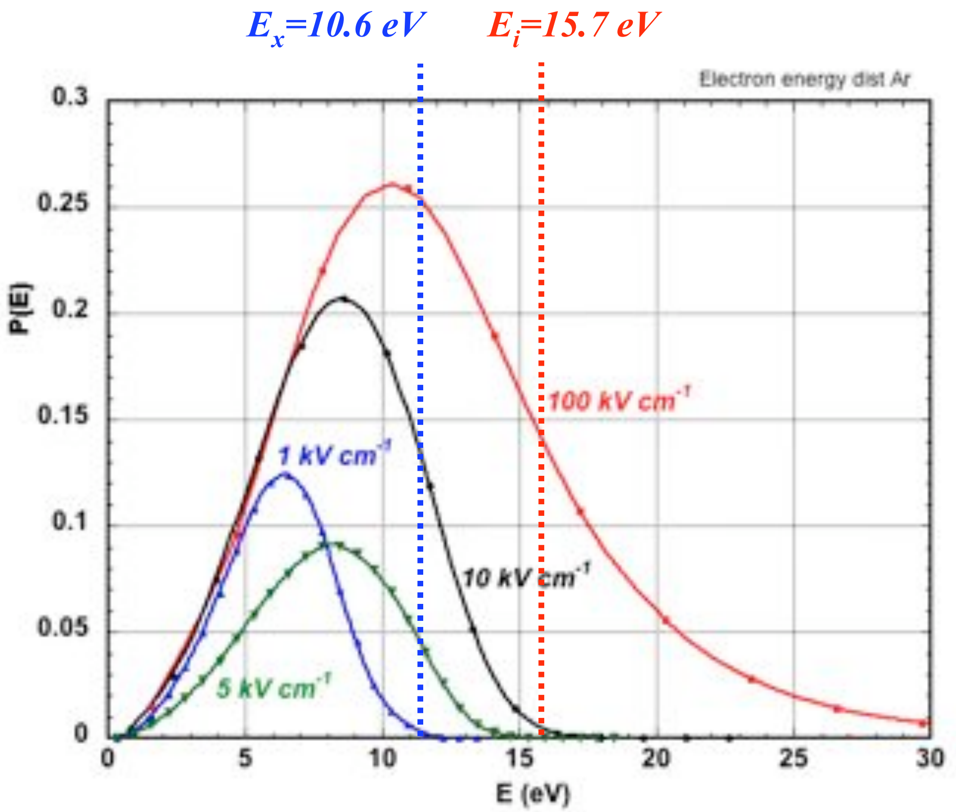


HIGH FIELD-INELASTIC COLLISIONS

ELECTRON CROSS SECTIONS IN ARGON:



ELECTRONS ENERGY DISTRIBUTION IN ARGON AT INCREASING FIELDS:



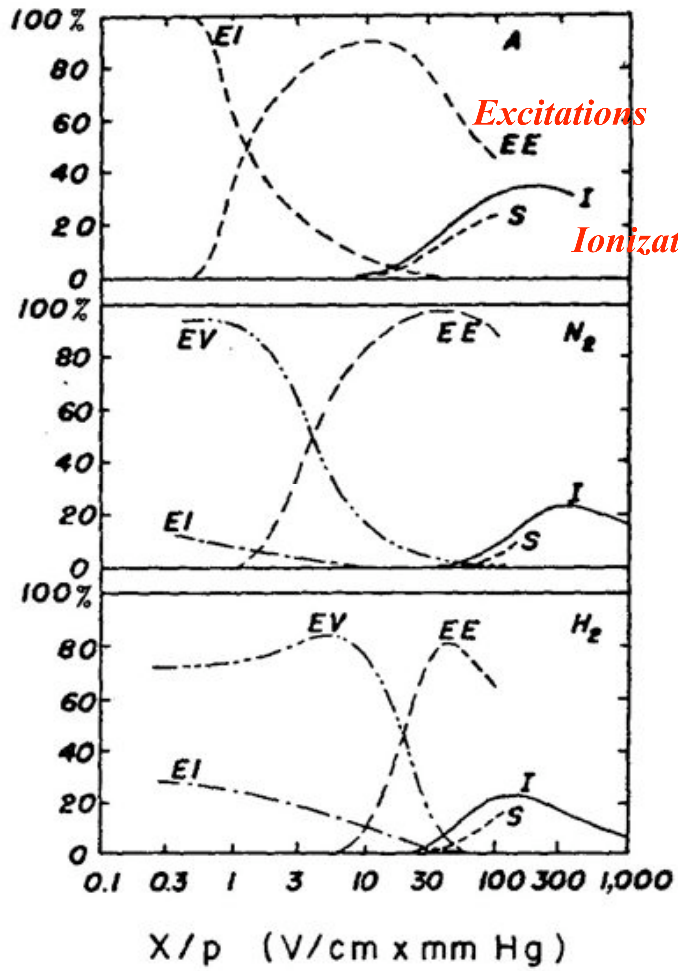
HIGH FIELD-INELASTIC COLLISIONS

MAIN ELECTRON-MOLECULE INELASTIC PROCESSES:

1)	$A+e$	$\Rightarrow$	$A^{+}+e+e$	Ionisation by electronic impact.
2)	$A+e$	$\Rightarrow$	$A^{*}+e$	Excitation by electronic impact.
3)	$A^{*}+e$	$\Rightarrow$	$A+e$	Deexcitation by electronic collision.
4)	$A+h\nu$	$\Rightarrow$	A^{*}	Photo-excitation (absorption of light).
5)	A^{*}	$\Rightarrow$	$A+h\nu$	Photo-emission (radiative deexcitation).
6)	$A+h\nu$	$\Rightarrow$	$A^{+}+e$	Photoionisation.
7)	$A^{+}+e$	$\Rightarrow$	$A+h\nu$	Radiative recombination.
8)	$A^{+}+B+e$	$\Rightarrow$	$A+B$	Three body recombination.
9)	$A^{*}+B$	$\Rightarrow$	$A+B^{*}$	Collisional deexcitation.
10)	$A^{*}+B$	$\Rightarrow$	$A+B^{+}+e$	Penning effect.
11)	$A^{+}+B$	$\Rightarrow$	$A+B^{+}$	Charge exchange.
12)	$A^{+}+B$	$\Rightarrow$	$A^{+}+B^{+}+e$	Ionisation by ionic impact.
13)	$A+B$	$\Rightarrow$	$A^{*}+B$	Excitation by atomic impact.
14)	$A+B$	$\Rightarrow$	$A^{+}+B+e$	Ionisation by atomic impact.
15)	$A+e$	$\Rightarrow$	A^{-}	Formation of negative ions.
16)	A^{-}	$\Rightarrow$	$A+e$	Electrons release by negative ions.
17)	$A^{**}+A$	$\Rightarrow$	$A_2^{+}+e$	Associative ionisation.
18)	$A^{+}+2A$	$\Rightarrow$	$A_2^{+}+A$	Molecular ion formation.
19)	$A^{*}+A+A$	$\Rightarrow$	$A_2^{*}+A$	Excimer formation.
20)	A_2^{*}	$\Rightarrow$	$A+A+h\nu$	Radiative excimer dissociation.
21)	$(XY)^{*}$	$\Rightarrow$	$X+Y^{*}$	Dissociation.
22)	$(XY)^{+}+e$	$\Rightarrow$	$X+Y^{*}$	Recombinational dissociation

J.Meek and J. D. Cragg, Electrical Breakdown of Gases (Clarendon Press, Oxford 1953)

APPROXIMATE SHARING BETWEEN COLLISION PROCESSES:



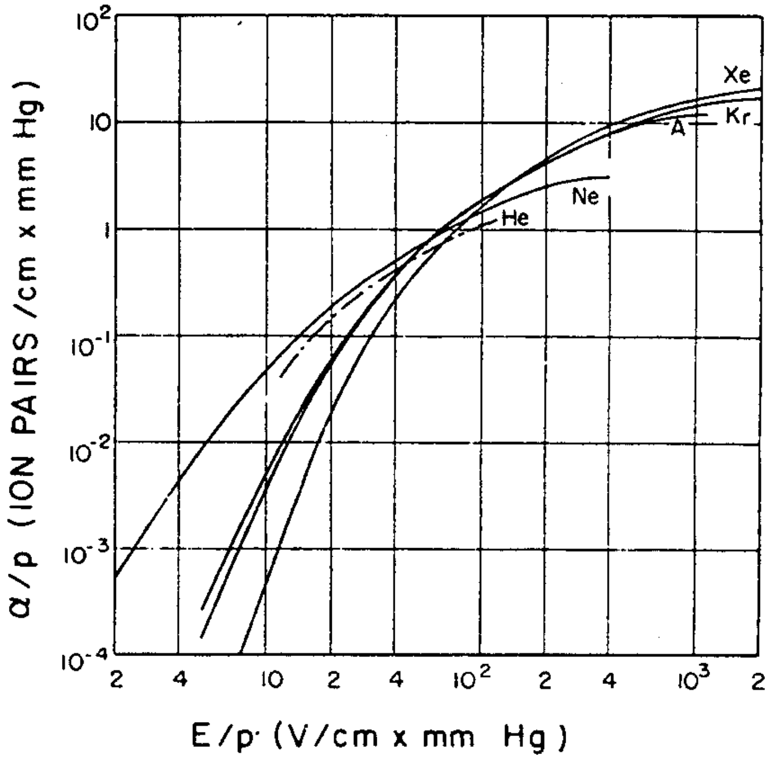
CHARGE MULTIPLICATION

Mean free path for ionization:

$$\lambda = \frac{1}{N\sigma} \qquad \textit{N: molecules/cm}^3$$

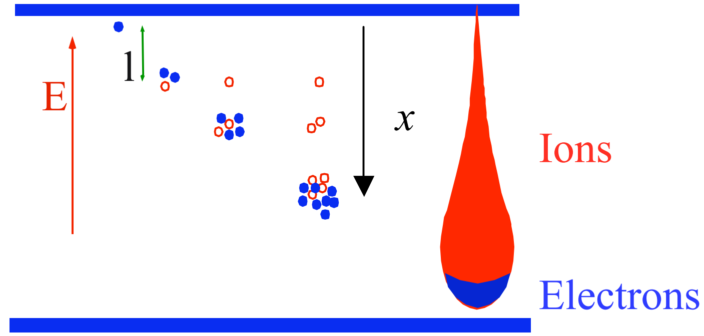
Townsend coefficient:

$$\alpha = \frac{1}{\lambda} \qquad \textit{Ionizing collisions/cm} \qquad \frac{\alpha}{P} = f\left(\frac{E}{P}\right)$$



S.C. Brown, Basic Data of Plasma Physics (MIT Press, 1959)

CHARGE MULTIPLICATION IN UNIFORM FIELD



Incremental increase of the number of electrons in the avalanche:

$$dn = n\,\alpha\,dx$$

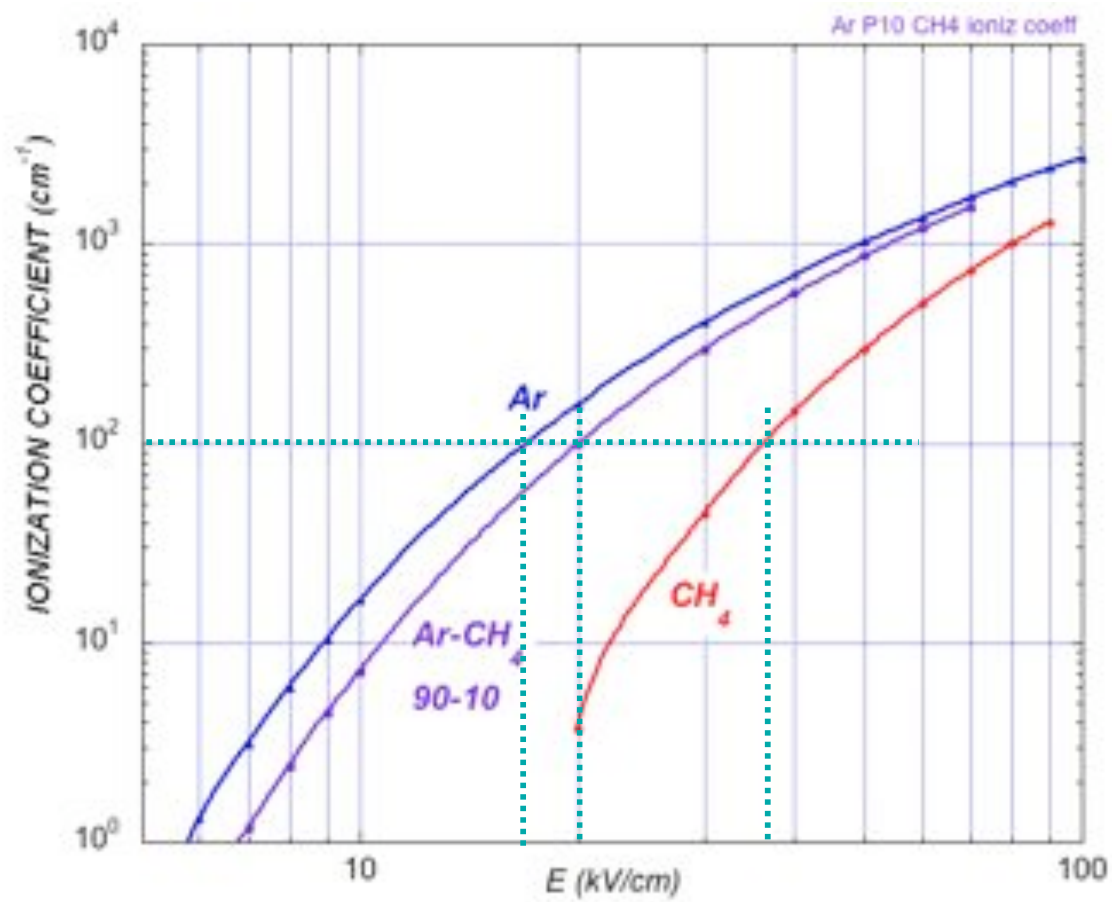
Multiplication factor or Gain: $M(x) = \frac{n}{n_0} = e^{\alpha x}$

Maximum Avalanche size before discharge (Raether limit):

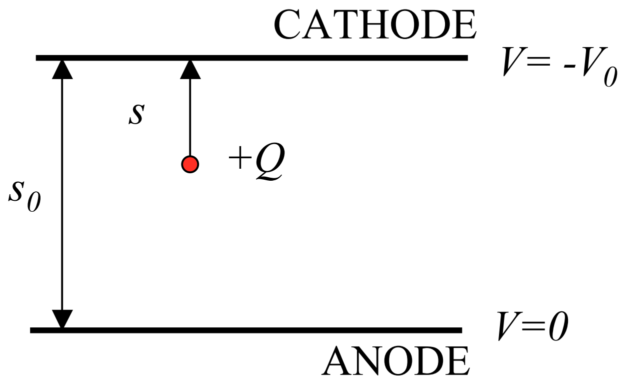
$$Q_{MAX} \approx 10^7 \text{ e}$$

H. Raether, Electron Avalanches and Breakdown in Gases (Butterworth 1964)

TOWNSEND COEFFICIENT FOR Ar-CH_4:
(MAGBOLTZ)



IONIZATION CHAMBER: SIGNAL DEVELOPMENT BY A MOVING CHARGE +Q



Charge induced on each electrode by +Q moving through the difference of potential dV:

$$dq = Q\frac{dV}{V_0} = Q\frac{ds}{s_0}$$

Integrating over s (or time t):

$$q(s) = \frac{Q}{s_0}s \qquad q(t) = \frac{Q}{s_0}wt \qquad i(t) = \frac{dq}{dt} = \frac{Q}{s_0}w$$

Electrons- ion pair (-Q and +Q) released at the same distance s from the cathode :

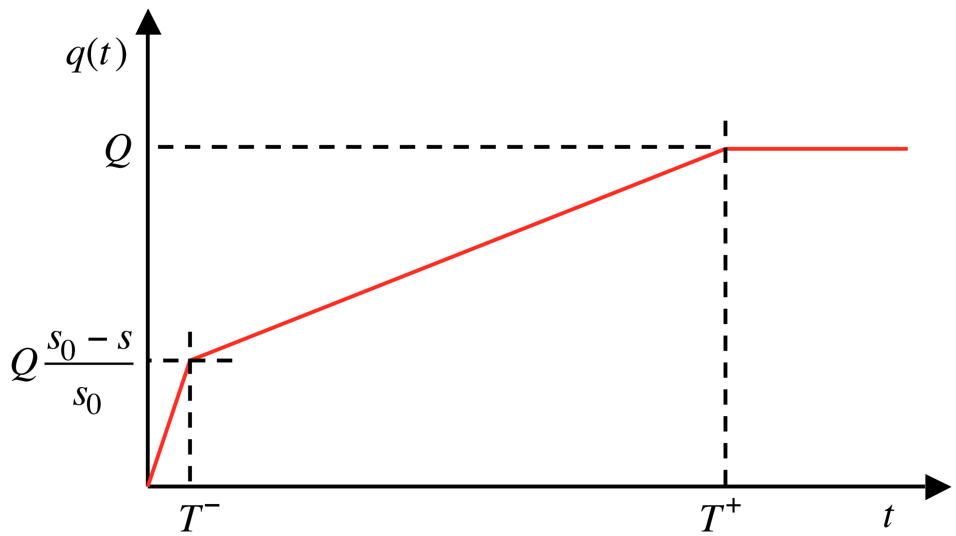
$$q(t) = Q\left(\frac{w^- t}{s_0} + \frac{w^+ t}{s_0}\right) \qquad 0 \le t \le T^-$$

$$q(t) = Q\left(\frac{s - s_0}{s_0} + \frac{w^+ t}{s_0}\right) \qquad T^- \le t \le T^+$$

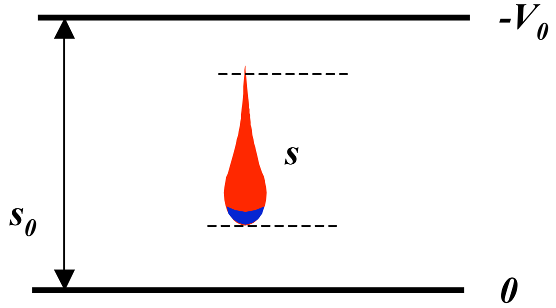
w^- (w^+) : electron (ion) drift velocity

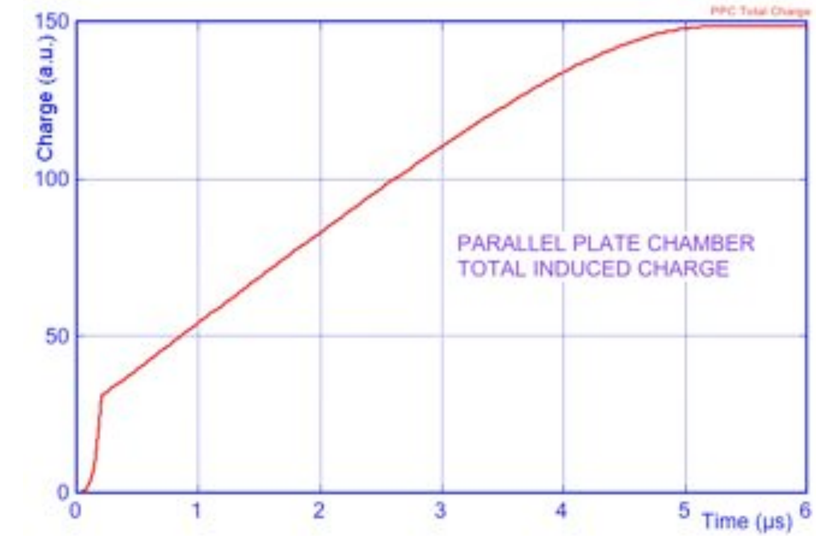
T^- (T^+) : total electron (ion) drift time

($+Q$ on cathode , $-Q$ on anode)



PARALLEL PLATE COUNTERS: SIGNAL DEVELOPMENT WITH CHARGE MULTIPLICATION





Increase in the number of charges after a path ds:

$$dn = n\alpha ds \qquad n = n_0 e^{\alpha s}$$

Charge induced by electrons: $dq^- = -en_0 e^{\alpha s}\dfrac{ds}{s_0}$

$$q^-(s) = \frac{en_0}{\alpha s_0}(e^{\alpha s} - 1) \approx \frac{en_0}{\alpha s_0}e^{\alpha s} = \frac{en_0}{\alpha s_0}e^{\alpha w^- t}$$

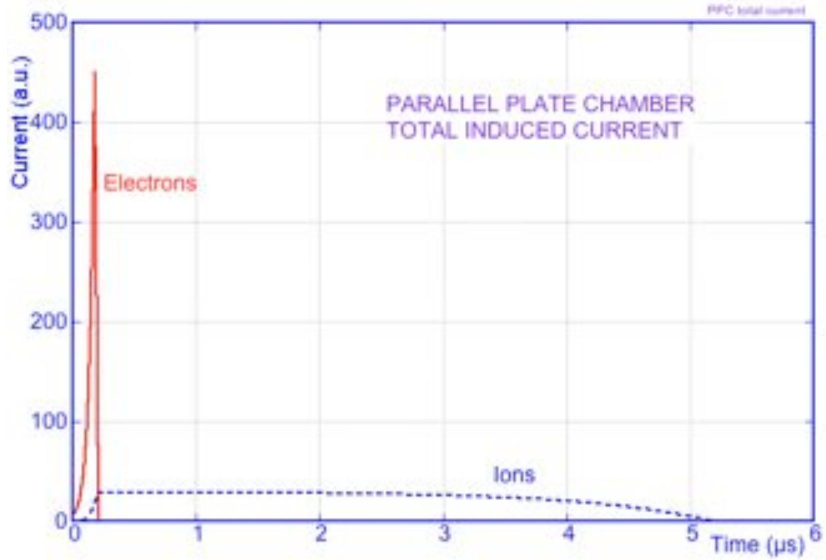
$$i^-(t) = \frac{dq^-}{dt} = \frac{en_0 w^-}{s_0}e^{\alpha w^- t} = \frac{en_0}{T^-}e^{\alpha w^- t}$$

Current signal induced by ions:

$$i^+(t) = \frac{en_0}{T^+}\left(e^{\alpha w^- t} - e^{\alpha w^* t}\right) \quad 0 \le t \le T^-$$

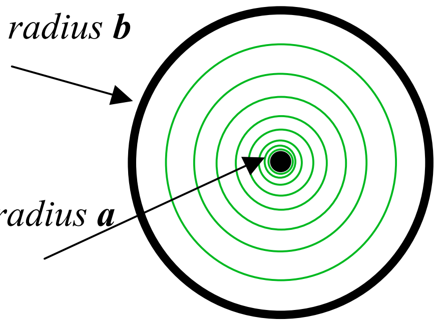
$$i^+(t) = \frac{en_0}{T^+}\left(e^{\alpha s} - e^{\alpha w^* t}\right) \quad T^- \le t \le T^+$$

$$\frac{1}{w^*} = \frac{1}{w^+} + \frac{1}{w^-}$$



PROPORTIONAL COUNTER

THIN ANODE WIRE

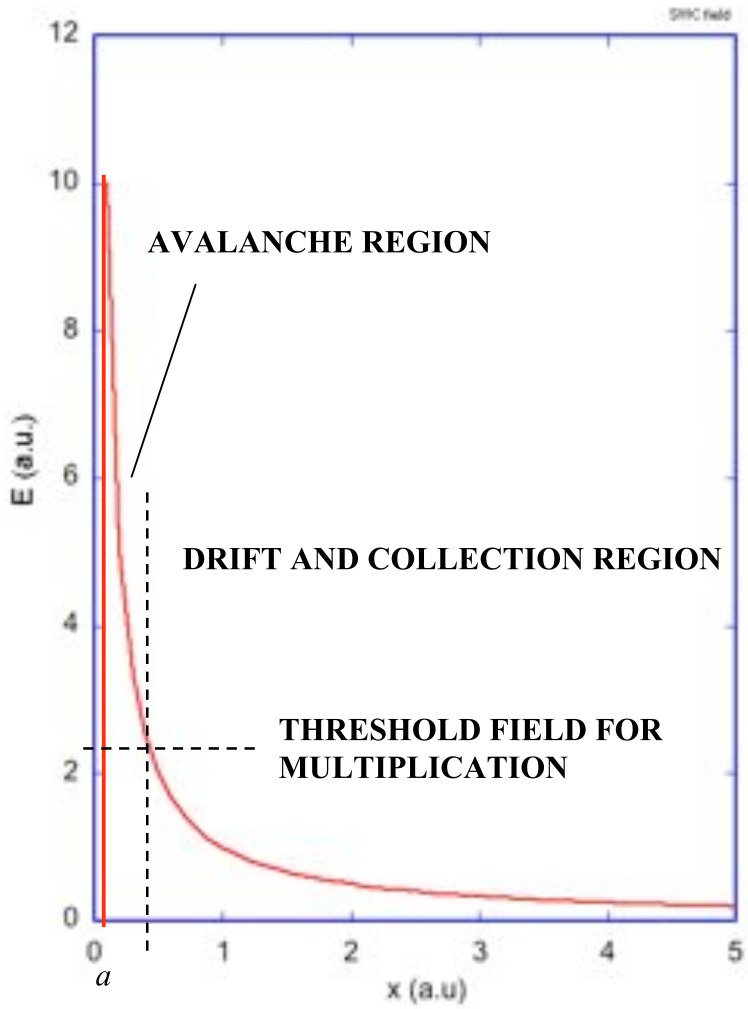


ELECTRIC FIELD AND POTENTIAL:

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

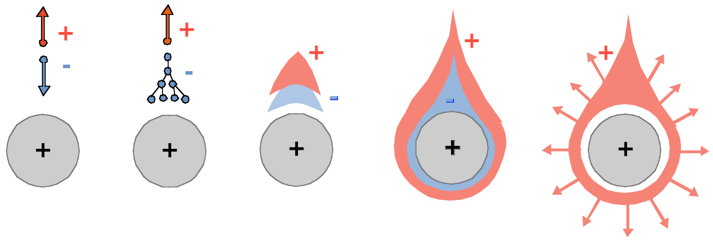
$$V(r) = \frac{CV_0}{2\pi\varepsilon_0}\ln\frac{r}{a}$$

$$C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$ capacitance per unit length



PROPORTIONAL COUNTER

AVALANCHE DEVELOPMENT:



CHARGE SIGNAL INDUCTION:

$$q^- = \frac{Q}{V_0}\int_a^{a+\lambda}\frac{dV}{dr}dr = -\frac{QC}{2\pi\varepsilon_0}\ln\frac{a+\lambda}{a}$$

$$q^+ = \frac{Q}{V_0}\int_{a+\lambda}^{b}\frac{dV}{dr}dr = -\frac{QC}{2\pi\varepsilon_0}\ln\frac{b}{a+\lambda}$$

$$q = q^- + q^+ = -\frac{QC}{2\pi\varepsilon_0}\ln\frac{b}{a} = -Q$$

λ: distance of avalanche start

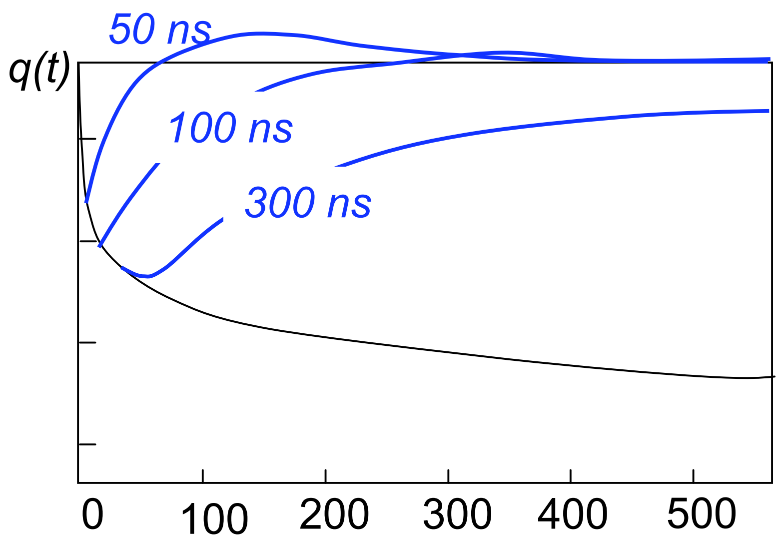
$$\frac{q^-}{q^+} = \frac{\ln(a+\lambda)-\ln a}{\ln b - \ln(a+\lambda)} \approx 0.01$$

99% of signal due to positive ions

$$q(t) = -\frac{QC}{2\pi\varepsilon_0}\ln\left(1+\frac{\mu^+ C V_0}{2\pi\varepsilon_0 a^2}t\right) = -\frac{QC}{2\pi\varepsilon_0}\ln\left(1+\frac{t}{t_0}\right)$$

CHARGE SIGNAL: POSITIVE ION TAIL

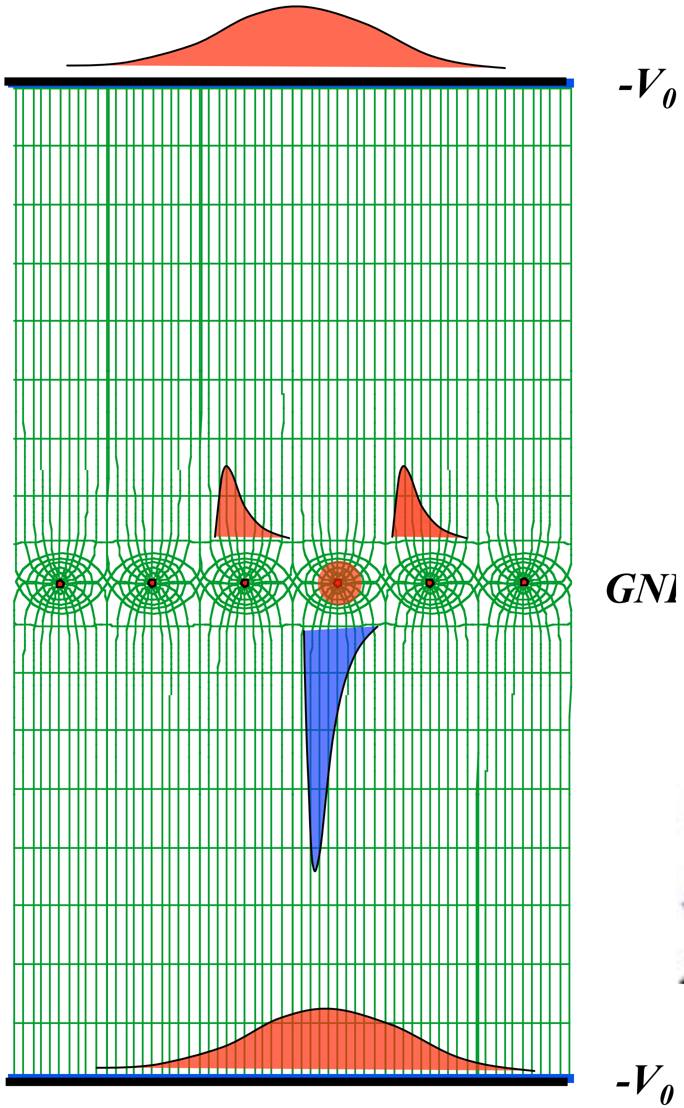
RC differentiation for faster response



S. C. Curran and J. D. Craggs, Counting Tubes (Butterworth 1949)

F. Sauli, Principles of Operation of Multiwire Proportional and Drift Chambers (CERN 77-09)

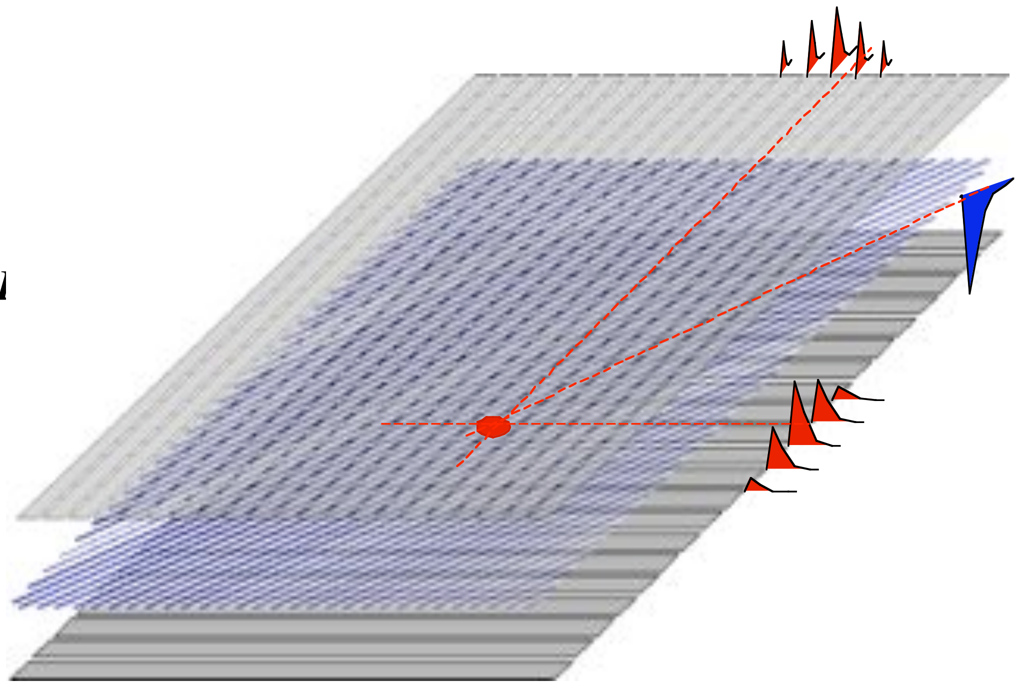
MULTIWIRE PROPRTIONAL CHAMBER



G. Charpak et al,
Nucl. Instr. and Meth. 62(1968)235

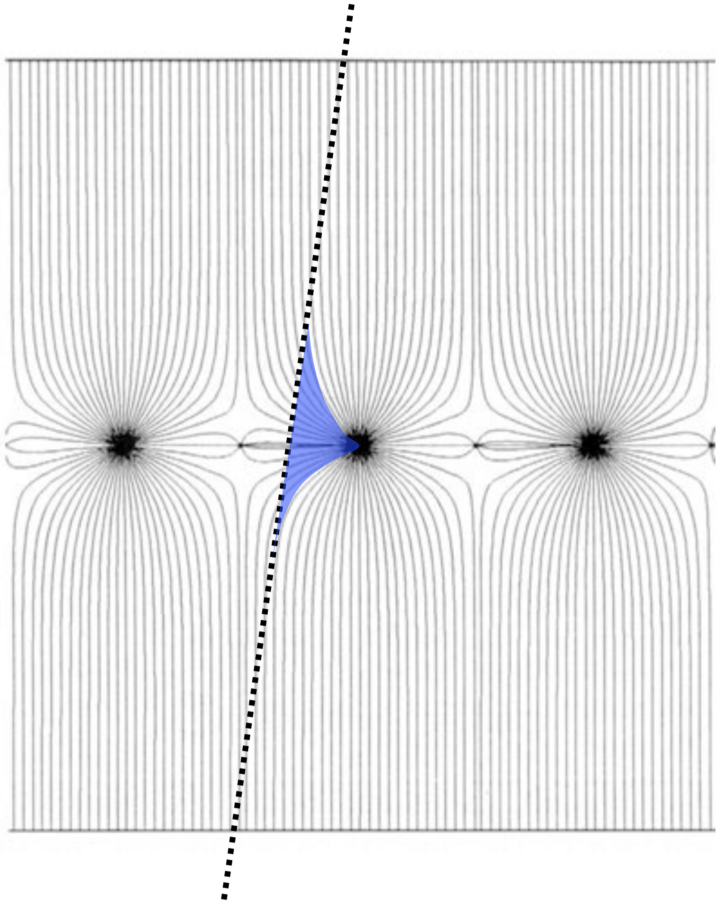
TWO-DIMENSIONAL COORDINATE READOUT
Center of gravity of induced signals on cathodes

$$X = \sum \frac{X_i\, A_i(X)}{A(X)} \qquad Y = \sum \frac{Y_i\, A_i(Y)}{A(Y)}$$

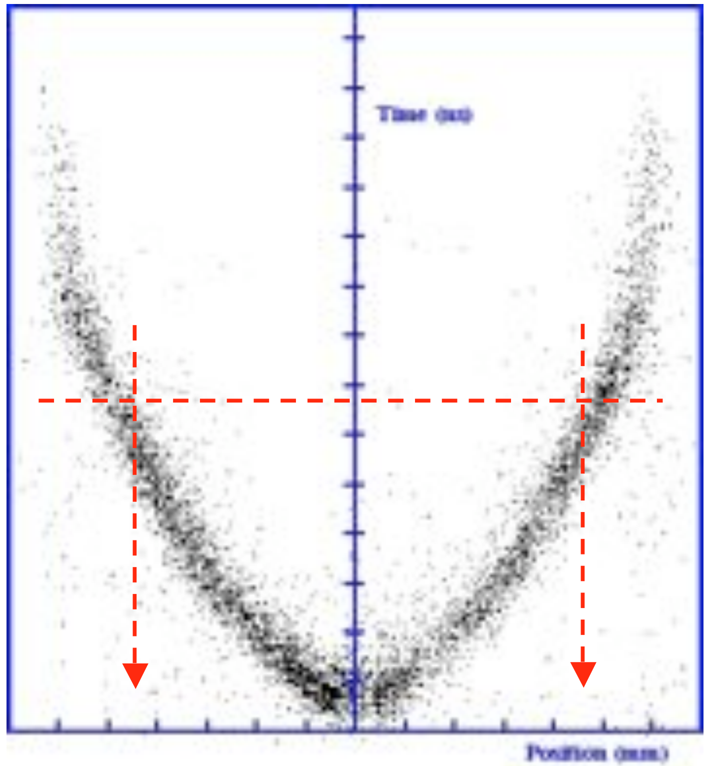


G. Charpak and F. Sauli,
Nucl. Instr. and Methods 113(1973)381

MWPC WITH A FIELD-SHAPING WIRE BETWEEN ANODES, TO AVOID LOW-FIELD REGIONS



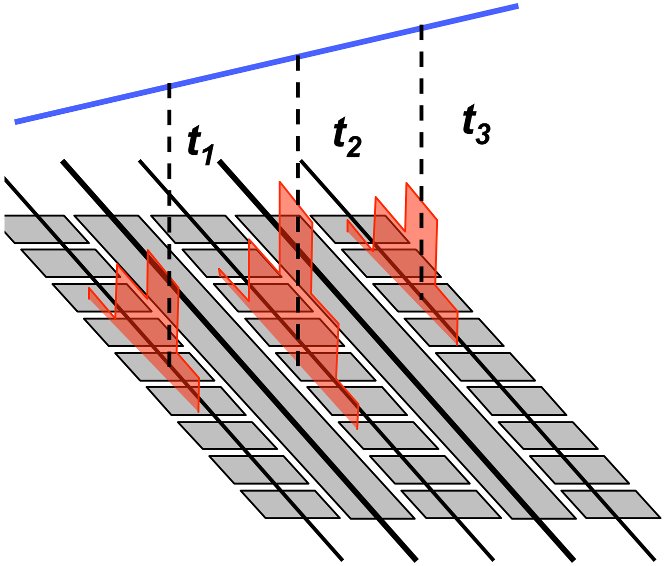
SPACE-TIME CORRELATION (RIGHT-LEFT AMBIGUITY):



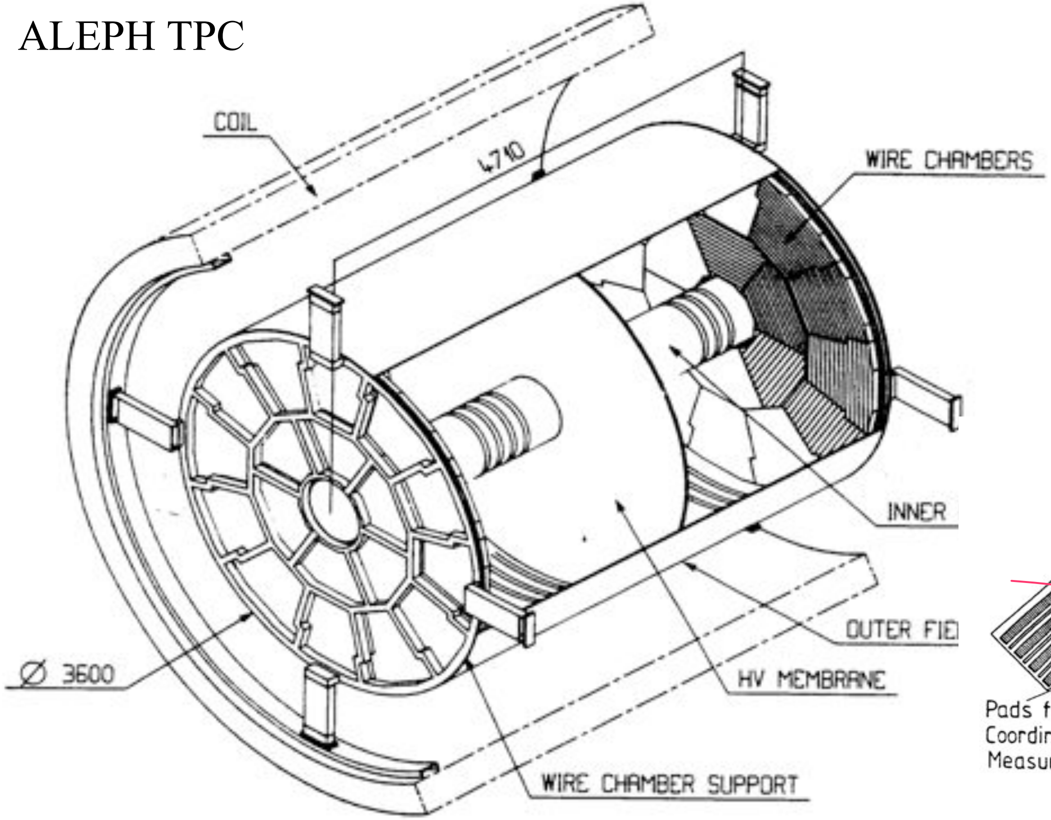
A. H. Walenta, J. Heintze and B. Scürlein, Nucl. Instr. and Meth. 92(1971)373

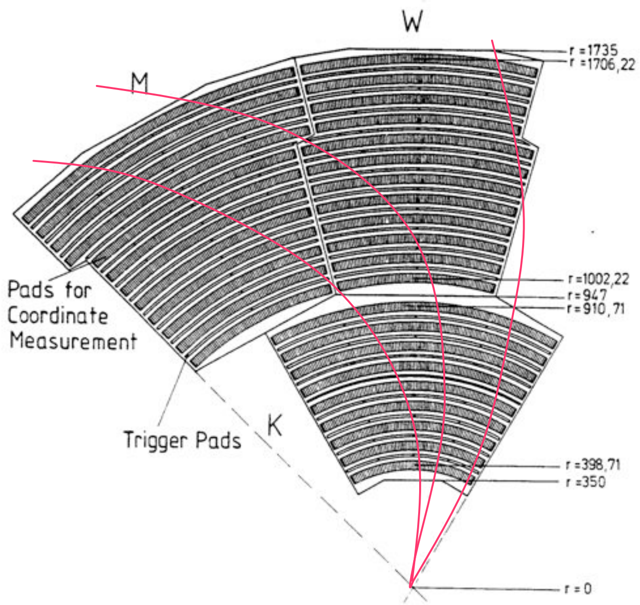
LARGE DRIFT VOLUME WITH END-CAP 2-D MWPC READOUT

D.R. Nygren and J. N. Marx, Physics Today No.31 Vol. 10(1978)



ALEPH TPC





D. Decamp et al, Nucl. Instr. and Meth. A294(1990)125

THE END

END OF THE LECTURES...

...BUT NOT OF THE FUN !