EDIT 2011

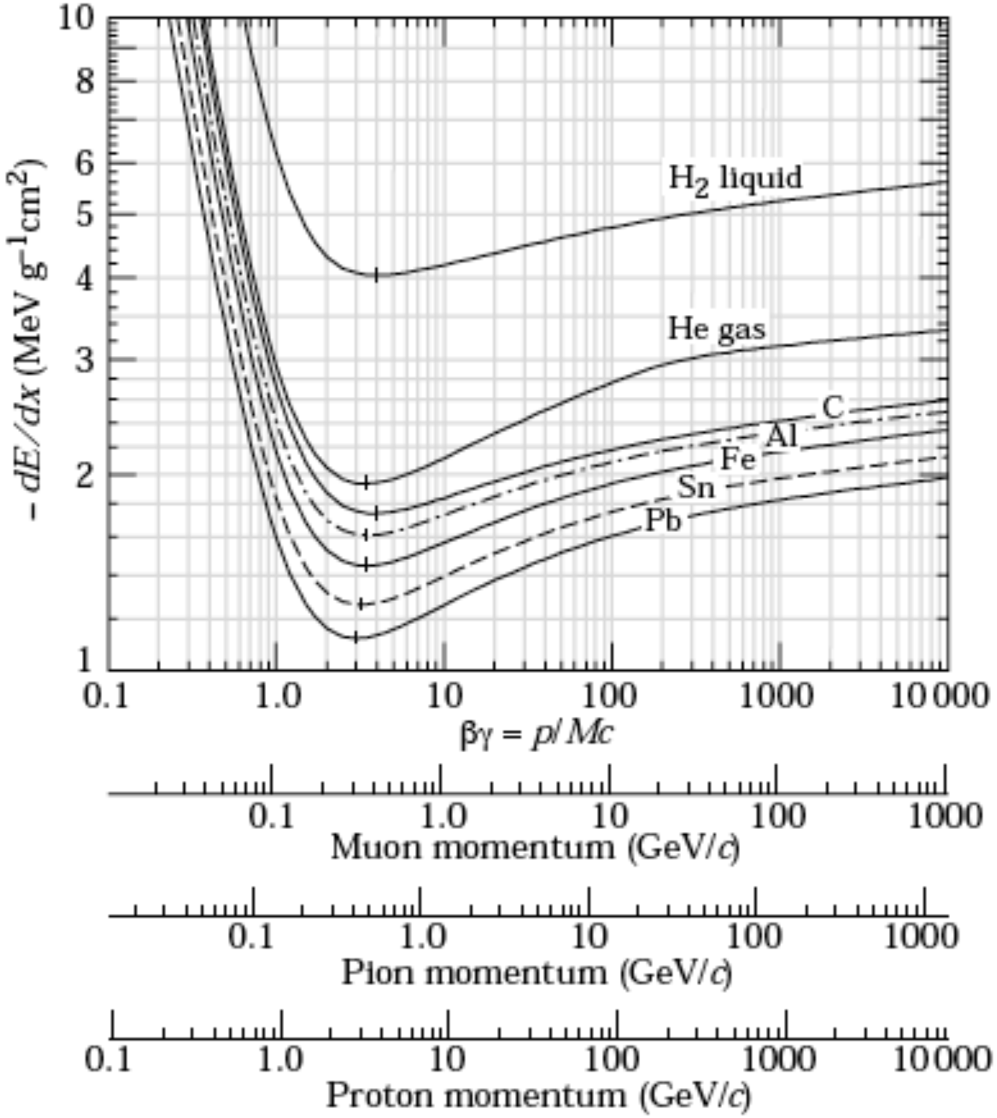
Excellence in Detectors and Instrumentation Technologies
CERN, Geneva, Switzerland - 31 January - 10 February 2011

GASEOUS DETECTORS FUNDAMENTS

Fabio Sauli
TERA Foundation and CERN

ENERGY LOSS OF CHARGED PARTICLES

DIFFERENTIAL ENERGY LOSS AS A FUNCTION OF VELOCITY



Reduced units:

$$\chi(g\,cm^{-2}) = \rho(g\,cm^{-3})\,l(cm)$$

$$\frac{dE}{d\chi} = \frac{1}{\rho}\frac{dE}{dx}$$ **ρ : density**

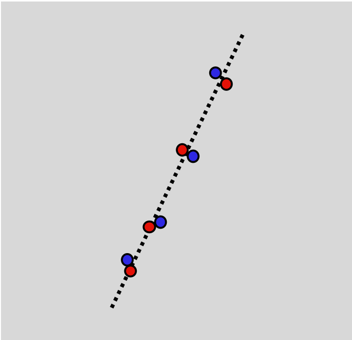
Expressed in MeV g^{-1} cm^2, the differential energy loss is equal within a factor of two for all materials (except H_2)

IONIZATION ENERGY LOSS OF CHARGED PARTICLES IN GASES

MAIN PARAMETERS:

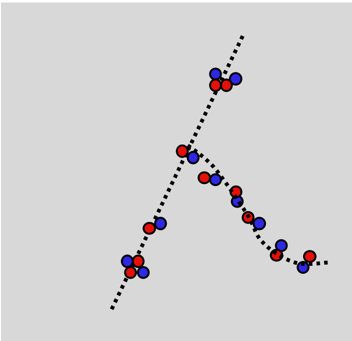
Gas	Density, $\mathrm{mg\,cm^{-3}}$	E_x eV	E_I eV	W_I eV	$dE/dx\|_{\min}$ $\mathrm{keV\,cm^{-1}}$	N_P $\mathrm{cm^{-1}}$	N_T $\mathrm{cm^{-1}}$
Ne	0.839	16.7	21.6	30	1.45	13	50
Ar	1.66	11.6	15.7	25	2.53	25	106
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	37	54
C_2H_6	1.26	8.2	11.5	26	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

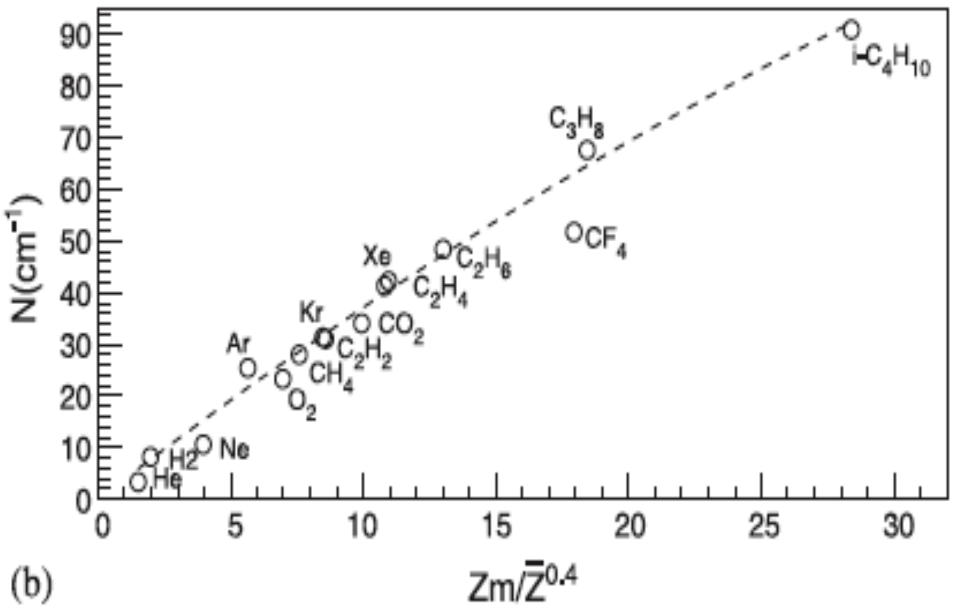
Total number of ion pairs: $n_T = \dfrac{\Delta E}{W_i}$

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

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

PRIMARY INTERACTIONS AND CLUSTERS

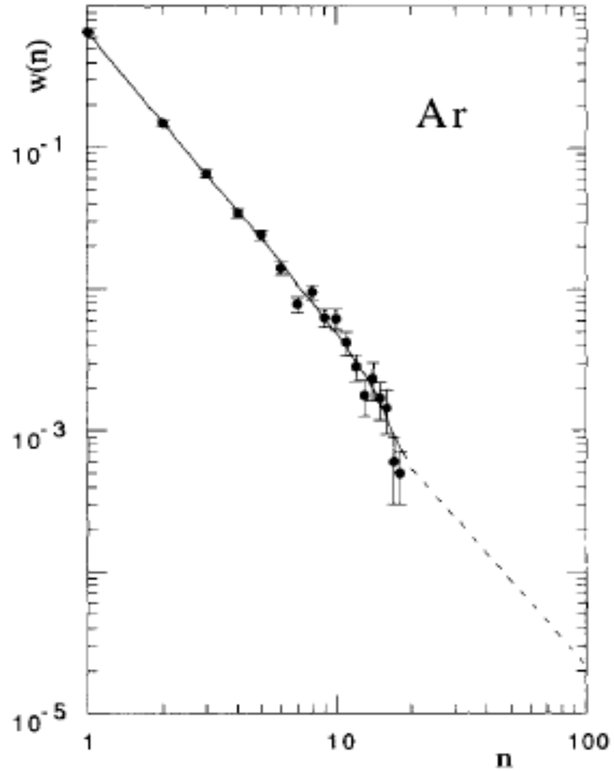
PROGRAM HEED:
NUMBER OF PRIMARY INTERACTIONS (CLUSTERS) IN GASES AT STP



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

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

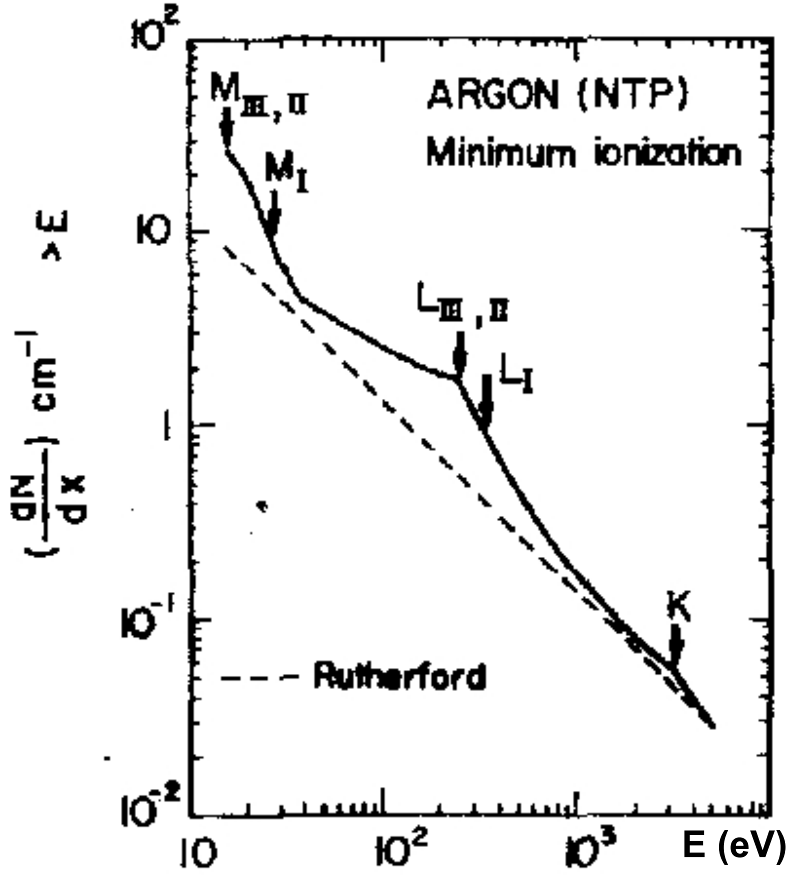
EXPERIMENTAL CLUSTER SIZE PROBABILITY:



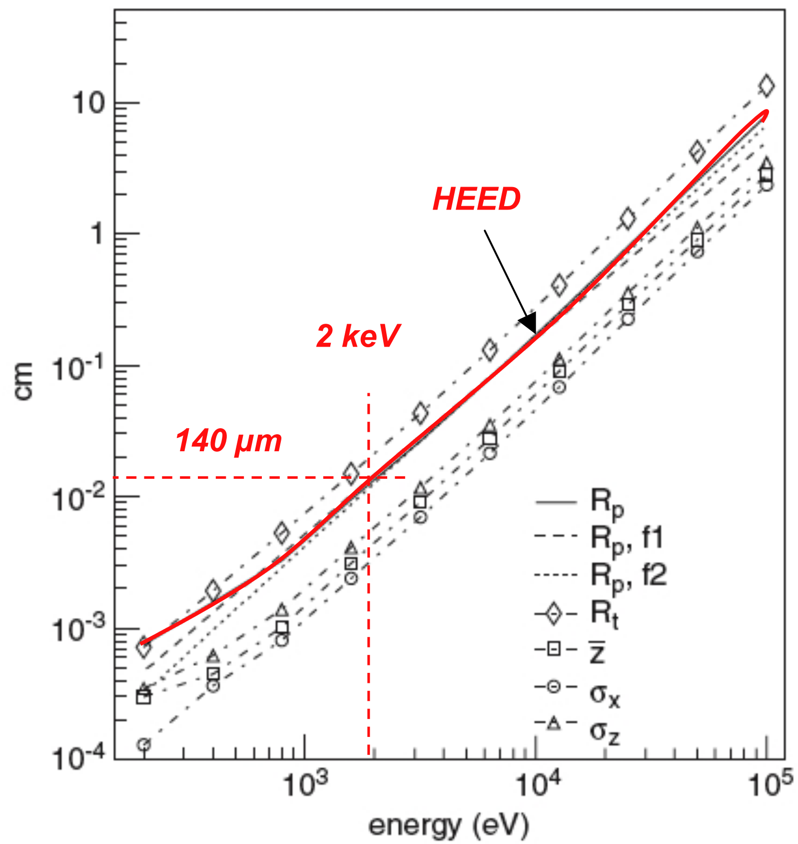
H. Fischle et al, Nucl. Instr. and Meth. A301 (1991) 202

PROBABILITY AND RANGE OF DELTA ELECTRONS

PROBABILITY FOR AN ELECTRON OF ENERGY > E:



ELECTRON RANGE IN ARGON STP:

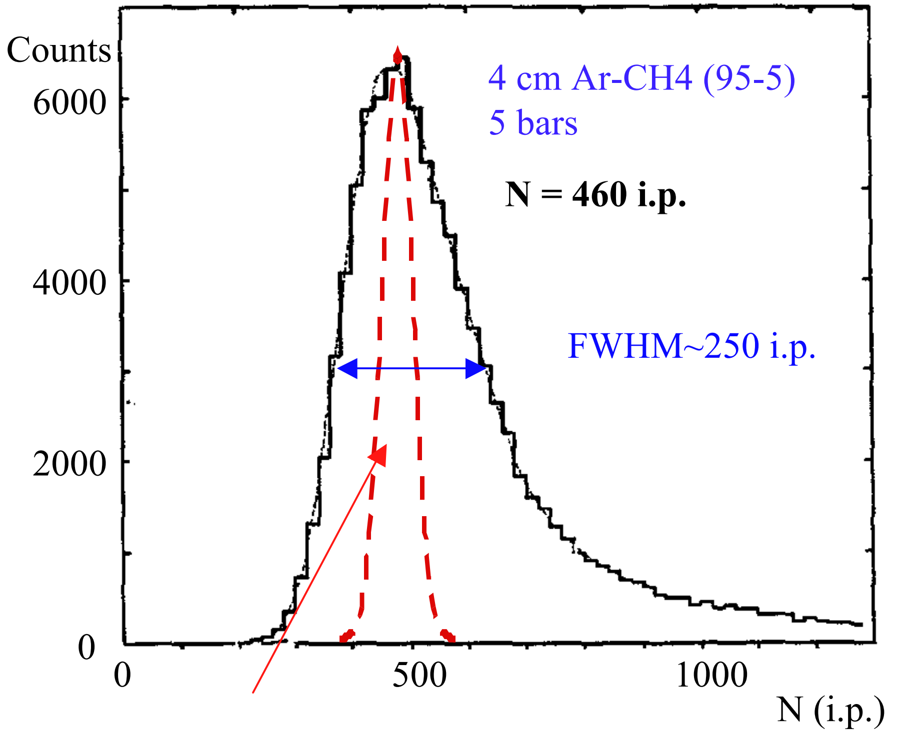


F. Lapique and F. Piuz,
Nucl. instr. and Meth. 175(1980)297

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

CONSEQUENCES OF IONIZATION STATISTICS

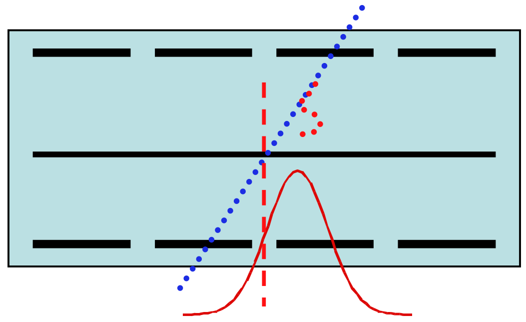
LANDAU DISTRIBUTION OF ENERGY LOSS:
POOR ENERGY LOSS RESOLUTION



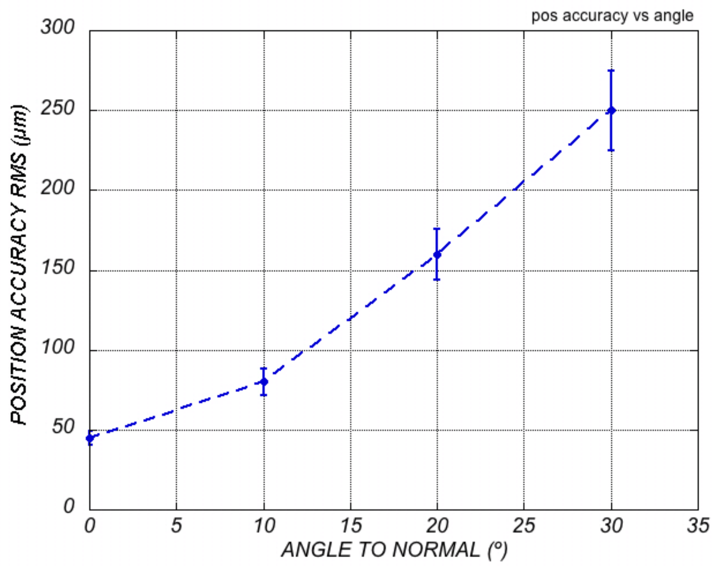
For a Gaussian distribution:

σ_N ~ 21 i.p. FWHM ~ 50 i.p.

STRONG ANGULAR DEPENDENCE
OF POSITION ACCURACY

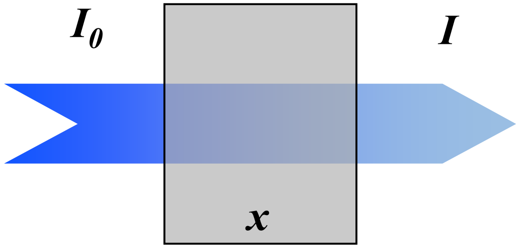


CENTER OF GRAVITY OF INDUCED CHARGE



G. Charpak et al, Nucl. Instr. and Meth. 167 (1979) 455

PHOTON ABSORPTION



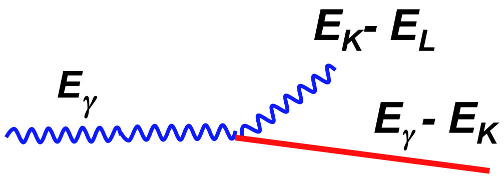
$$I = I_0 e^{-\frac{x}{l}}$$

l : absorption length

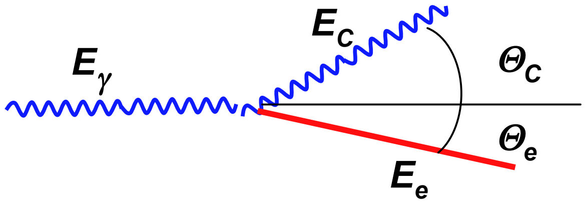
Conversion efficiency:

$$\varepsilon = \frac{I_0 - I}{I_0} = 1 - e^{-\frac{x}{l}}$$

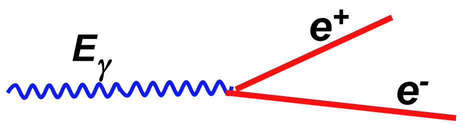
PHOTOELECTRIC: Interaction with an electronic shell with emission of a photoelectron. The excited atom/molecule returns to ground state through fluorescence or radiation-less (Auger) process.



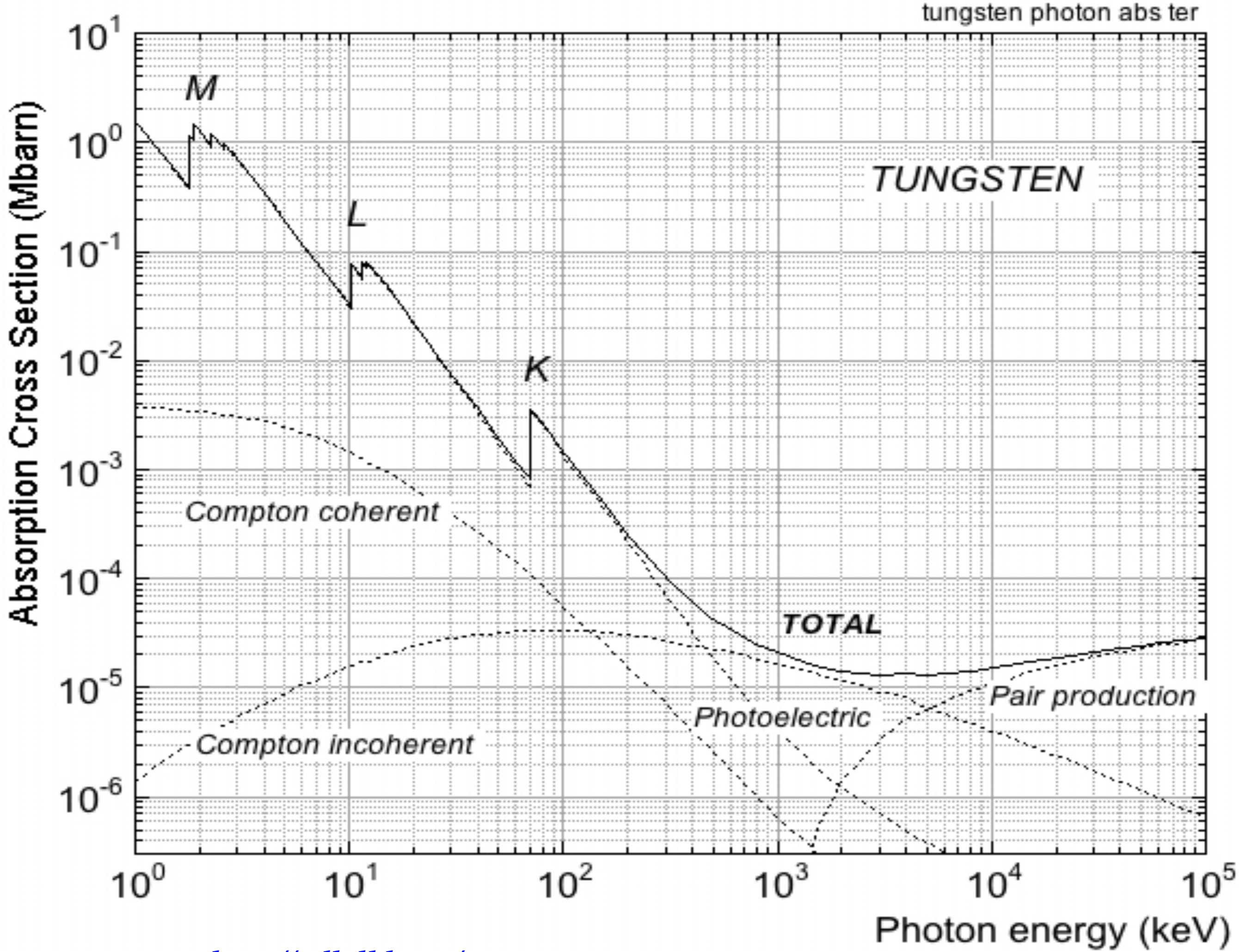
COMPTON: Scattering of the photon by quasi-free electrons; can be coherent or incoherent



PAIR PRODUCTION: Conversion in a e^+e^- pair in the field of the atom/molecule. Possible for $E_\gamma > 2\ m_e = 1.022$ MeV



DETECTION OF PHOTONS



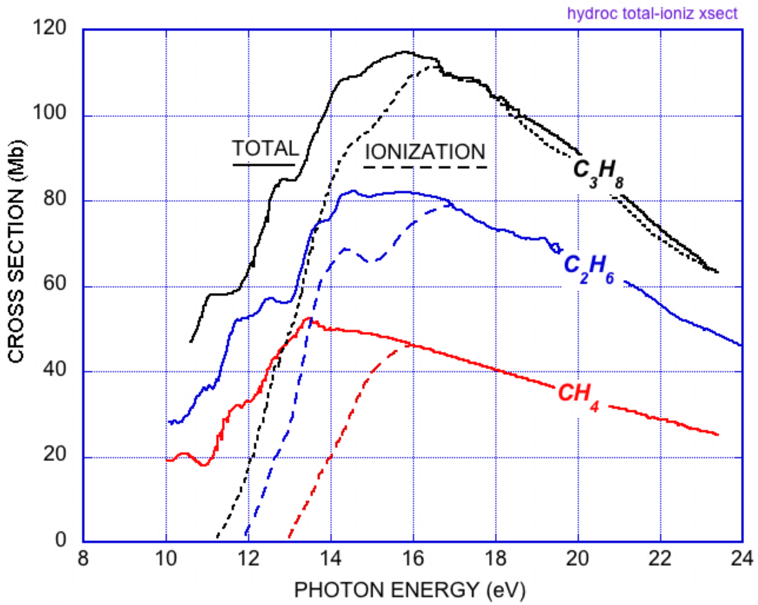
http://xdb.lbl.gov/

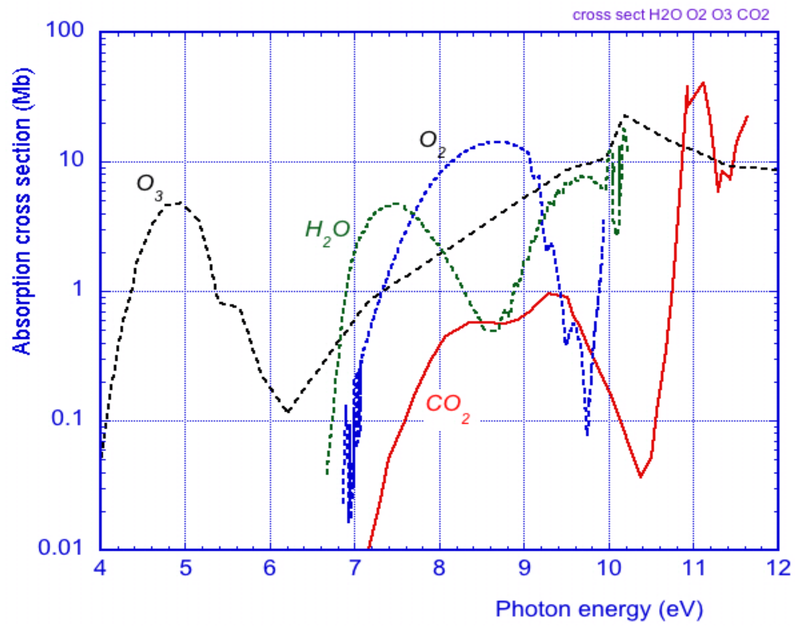
http://henke.lbl.gov/optical_constants/

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

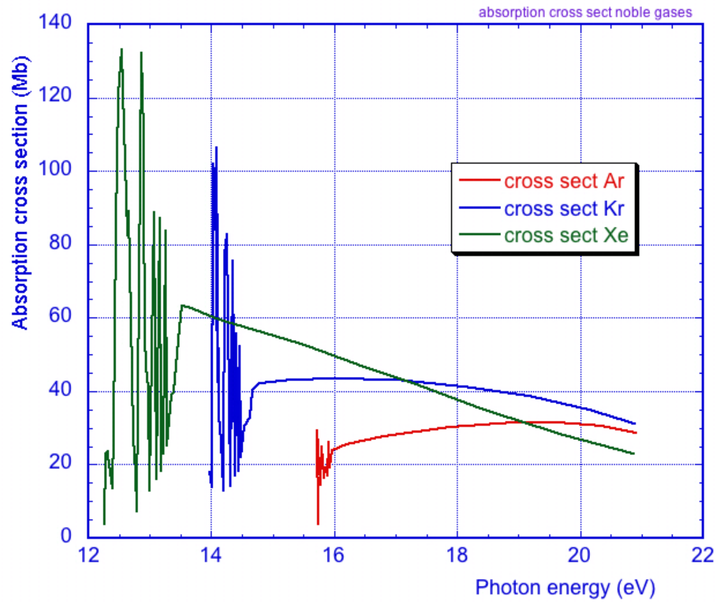
PHOTON ABSORPTION: VISIBLE TO ULTRAVIOLET

MOLECULAR GASES: ABSORPTION CROSS SECTIONS





NOBLE GASES:
PHOTOIONIZATION ABOVE THRESHOLD



H. S. W. Massey, Electronic and Ionic impact Phenomena (Oxford Press 1969)

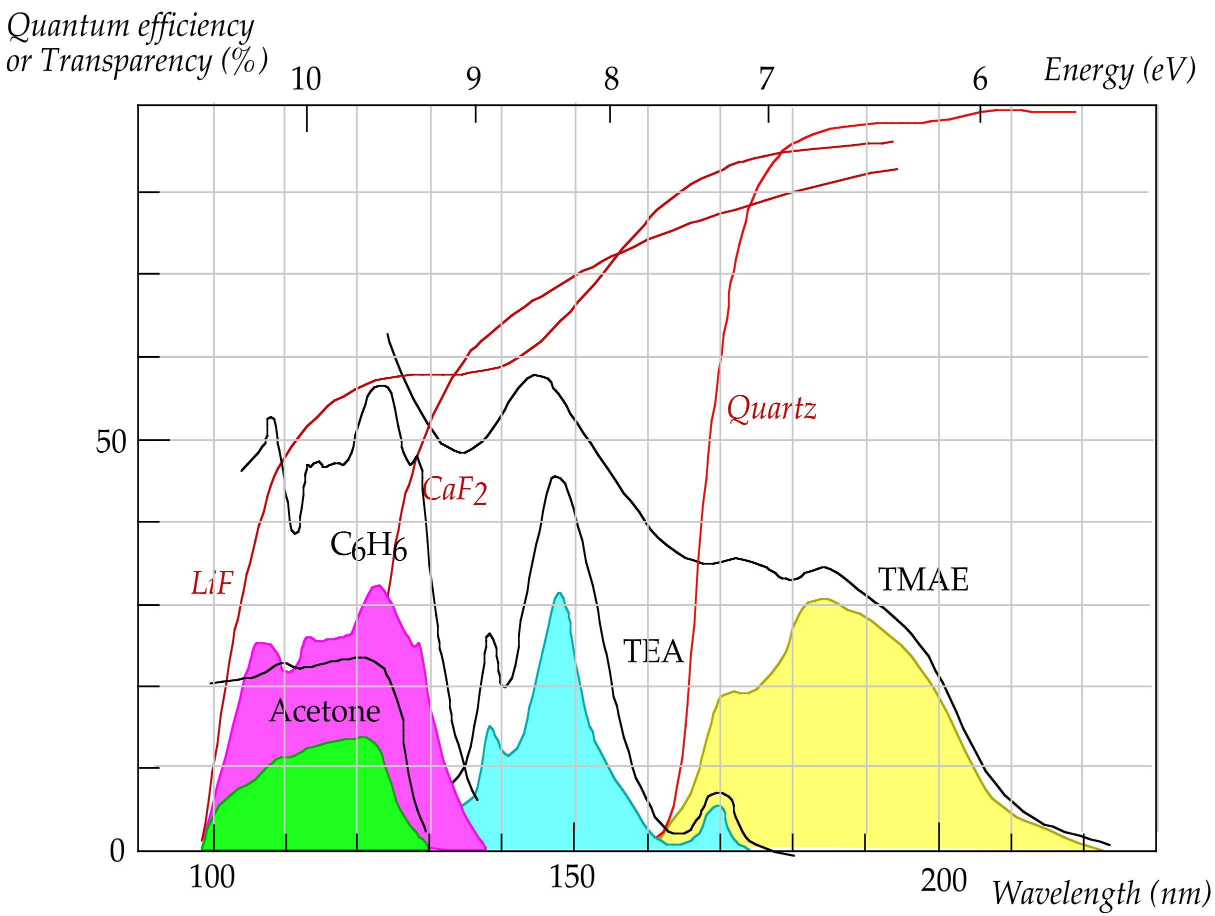
G. Marr, Photoionization Processes in Gases (Academic Press NY 1967)

PHOTOIONIZATION

PHOTOSENSITIVE VAPOURS:

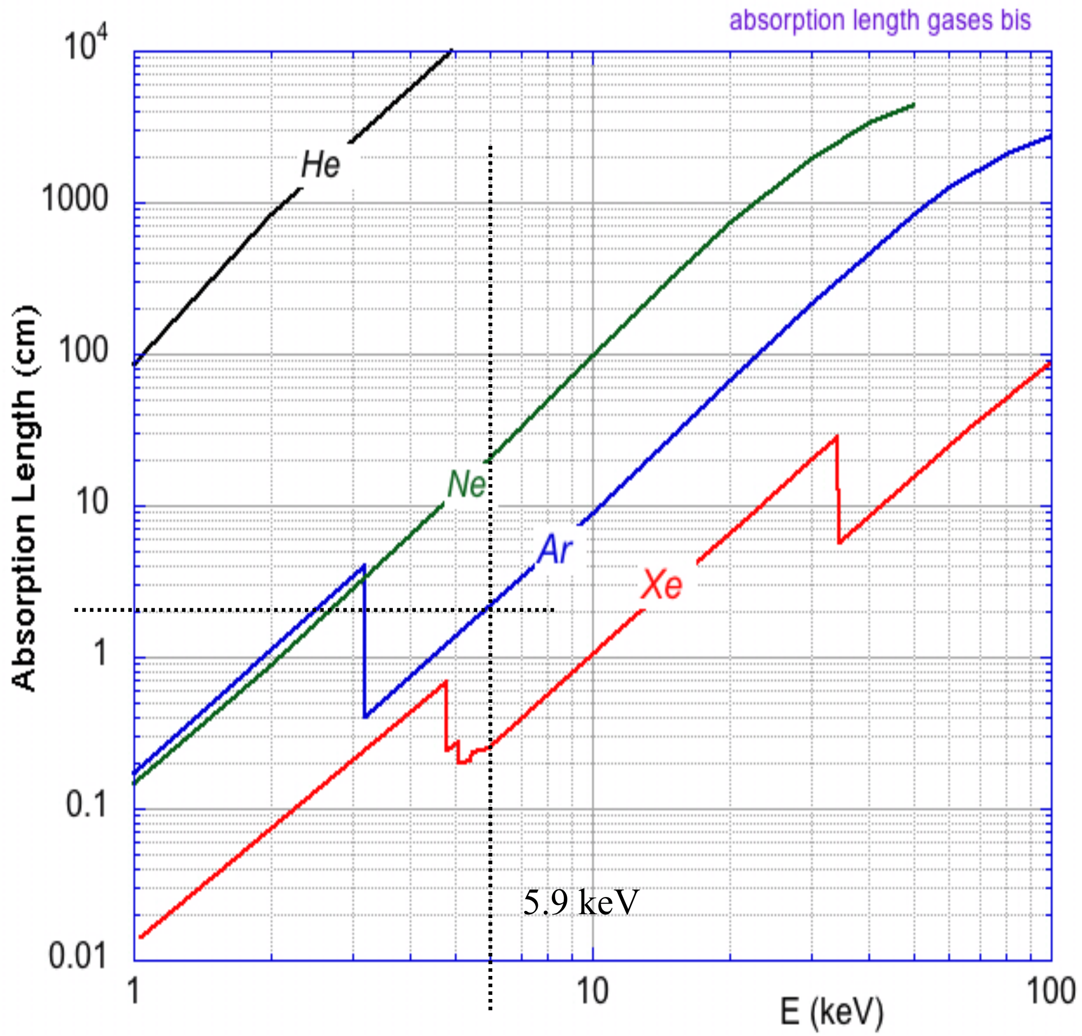
TEA (Triethylamine, $(C_2H_5)_3N$) E_i=7.5 eV

TMAE (Tetrakis (dimethylamine) ethylene, $[(CH_3)_2N]_2C$ E_i=5.6 eV



CHERENKOV RING IMAGING

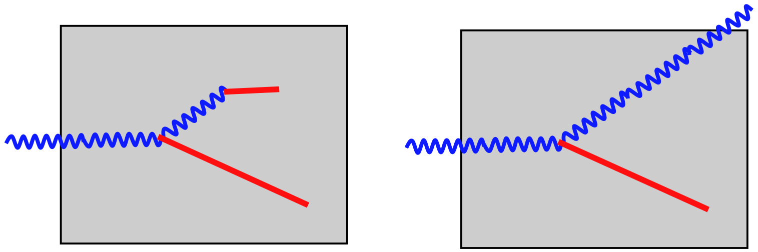
ABSORPTION LENGTH IN GASES (STP) VS PHOTON ENERGY



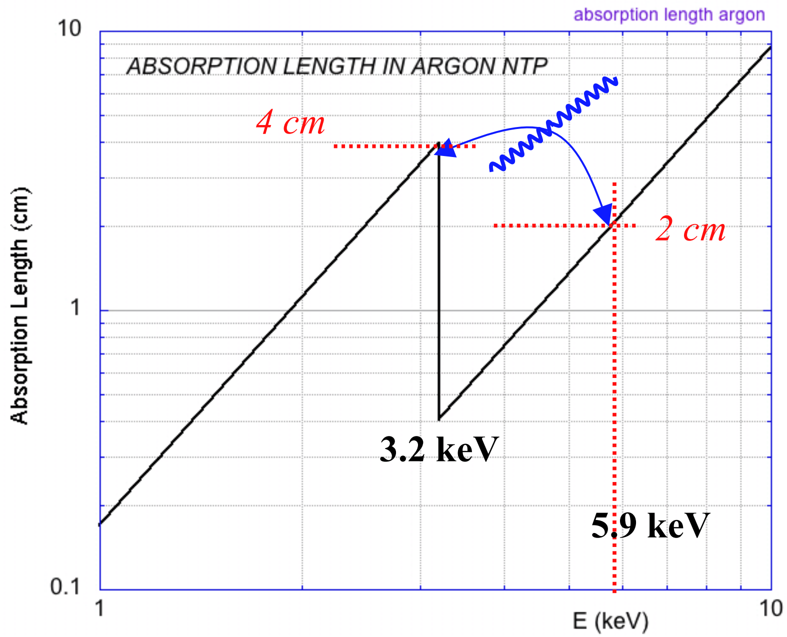
e.g.:
^{55}Fe 5.9 keV X-rays in Argon
l = 2 cm

In a 1 cm thick counter:
ε ~ 0.4

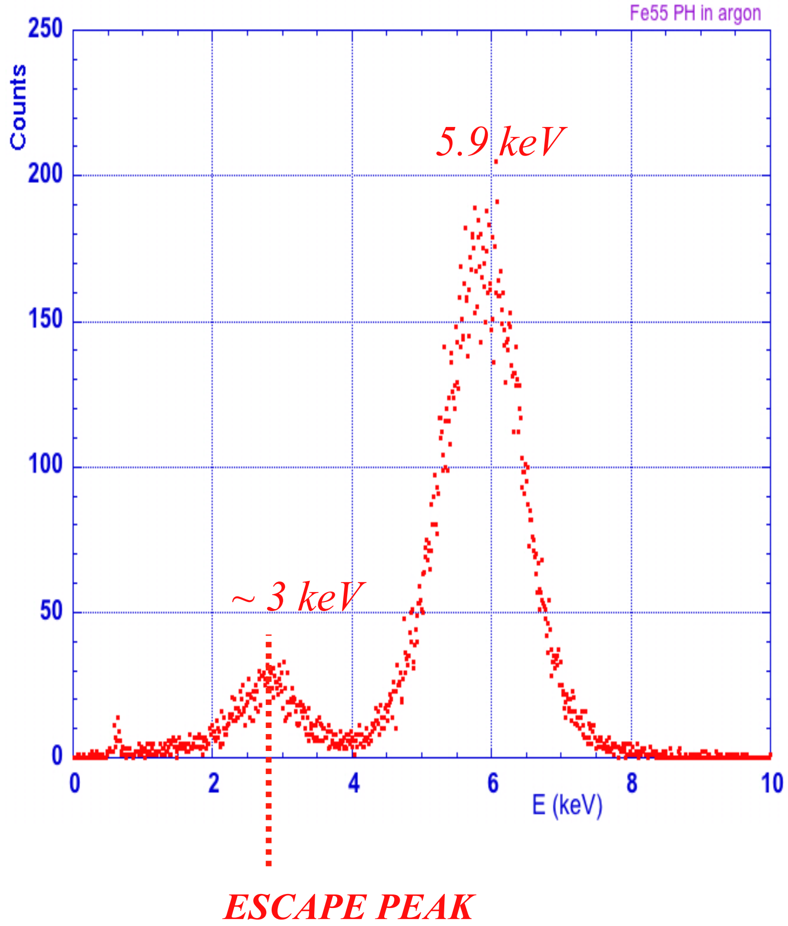
Fluorescence photons can convert far from the primary interaction, or escape from the sensitive volume (escape peak):



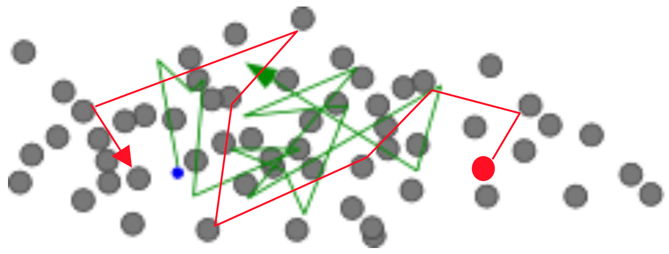
^{55}Fe 5.9 keV:

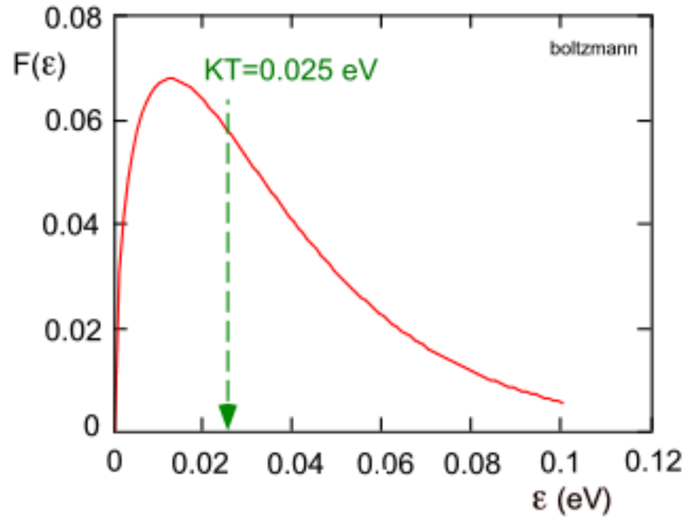


X-RAY ABSORPTION SPECTRUM
^{55}Fe X-Rays (5.9 keV) in Argon:



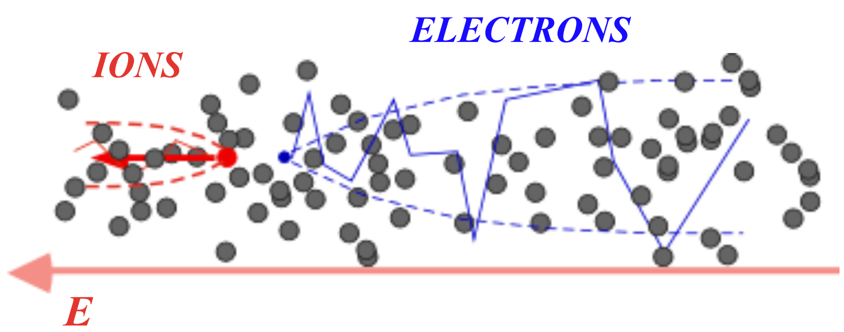
E = 0 : THERMAL DIFFUSION (Ions and electrons):

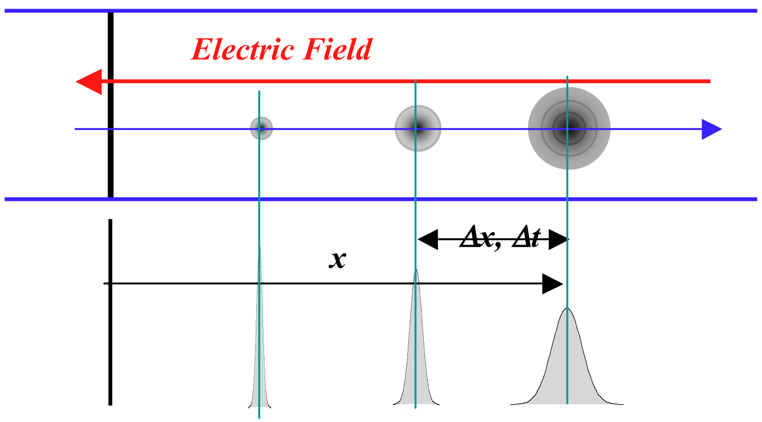




Maxwell energy distribution: $F(\varepsilon) = C\sqrt{\varepsilon}\, e^{-\frac{\varepsilon}{KT}}$

E > 0: CHARGE TRANSPORT AND DIFFUSION





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

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

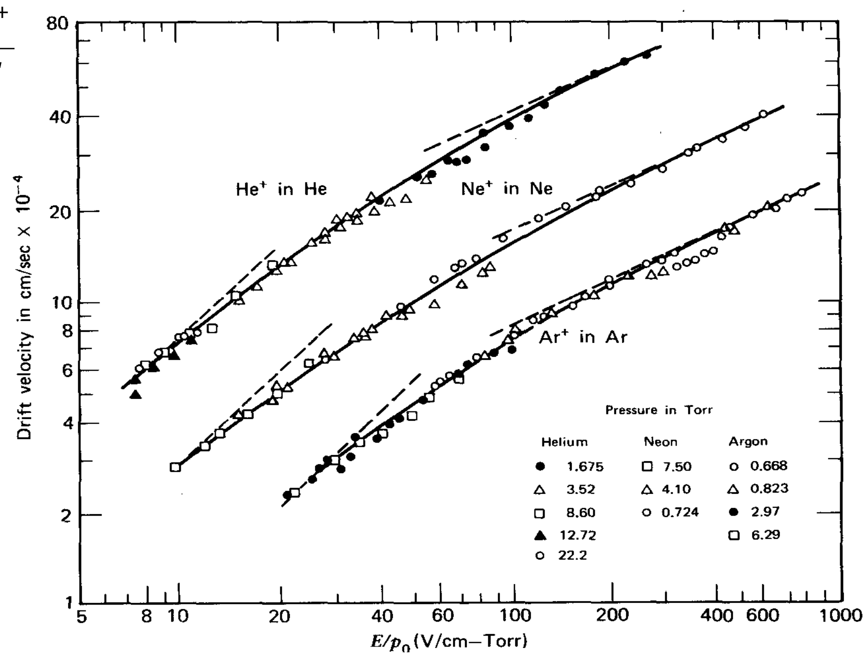
DRIFT OF IONS

MOBILITY: RATIO OF VELOCITY AND FIELD $\mu^+ = \frac{w^+}{E}$

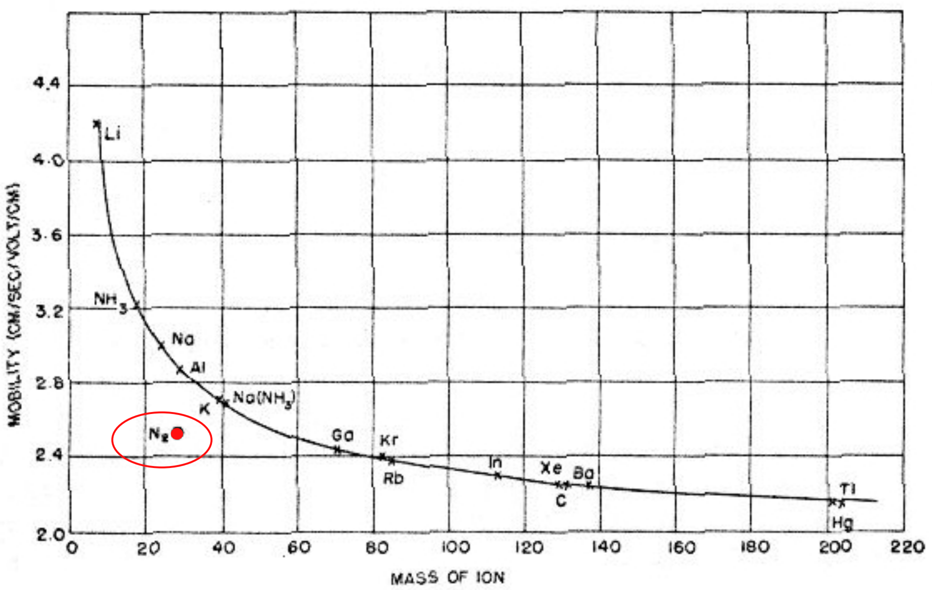
IONS MOBILITY (NTP: 300 K, 760 mm Hg)

GAS	ION	$\mu^+(cm^2s^{-1}V^{-1})$
He	He^+	10.2
Ar	Ar^+	1.7
CH_4	CH_4^+	2.26
Ar	CH_4^+	1.87
CO_2	CO_2^+	1.09

Ar-CH_4, E=1kV cm^{-1} w^+= 1.87 cm ms^{-1}



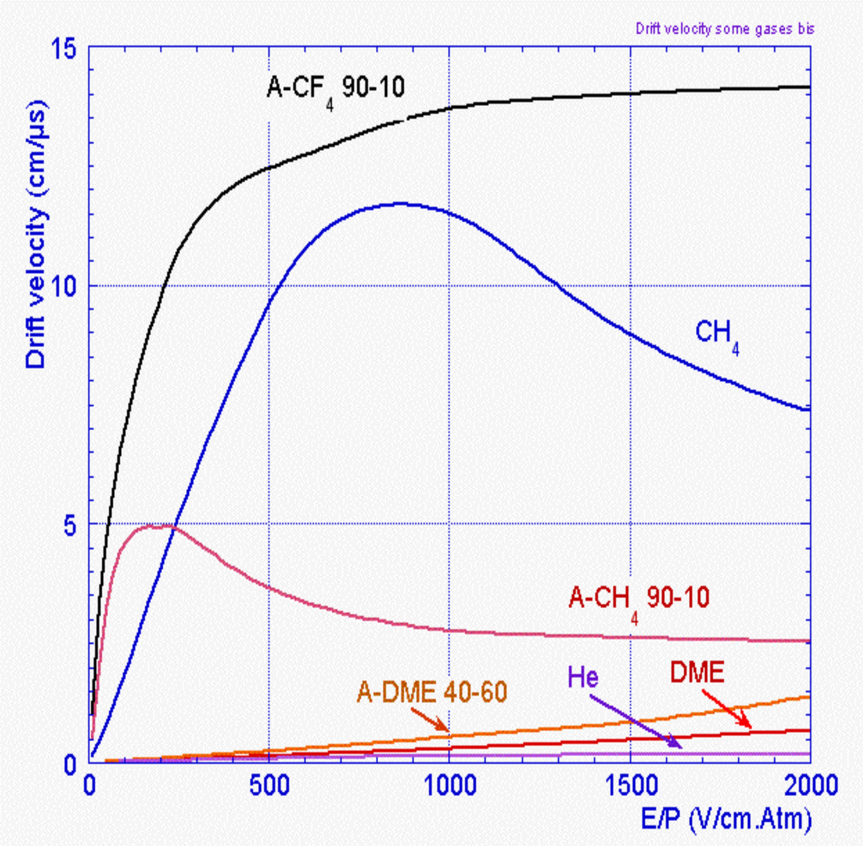
IONS MOBILITY IN NITROGEN:



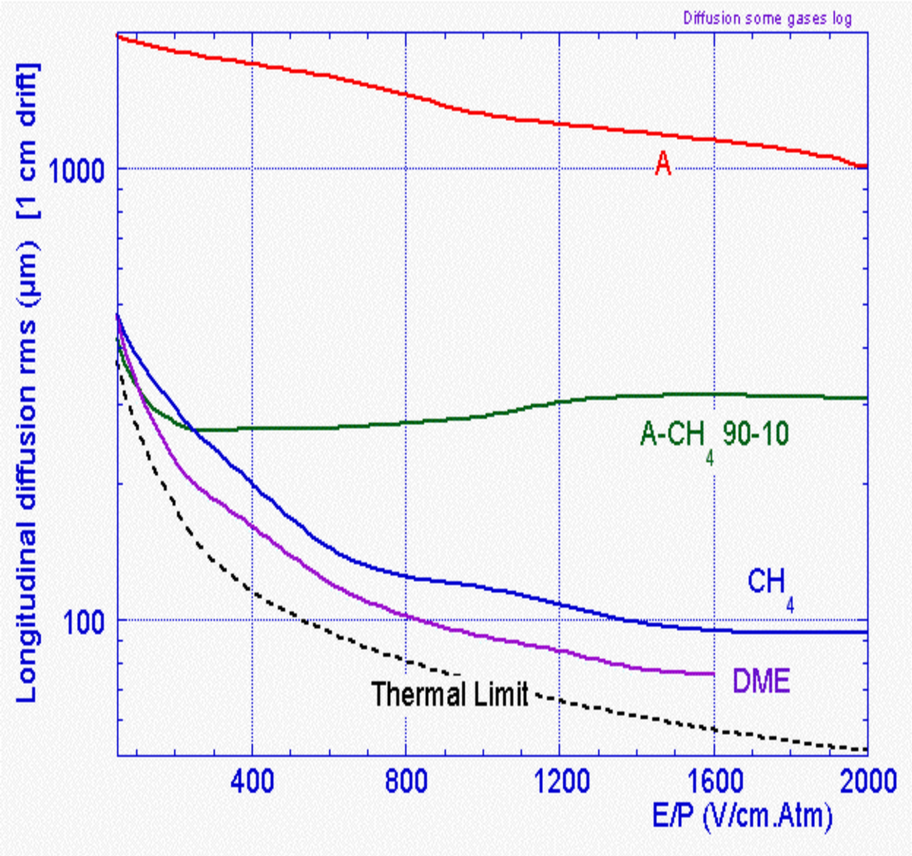
S. C. Brown
Basic Data in Plasma Physics (Wiley, New York 1959)

ELECTRONS DRIFT VELOCITY

DRIFT VELOCITY:



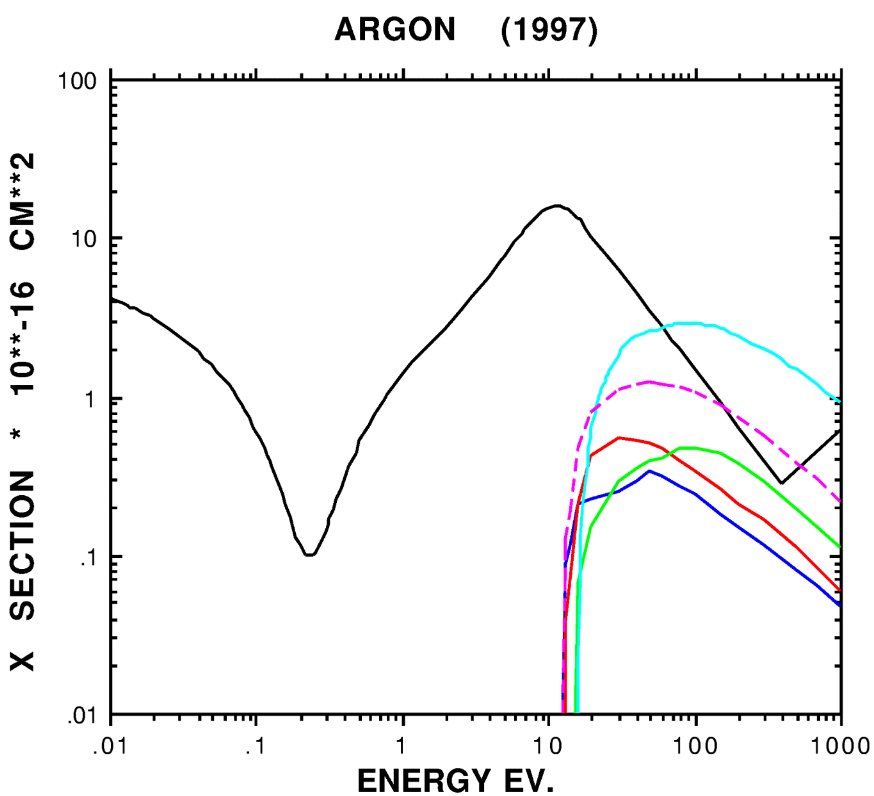
DIFFUSION:

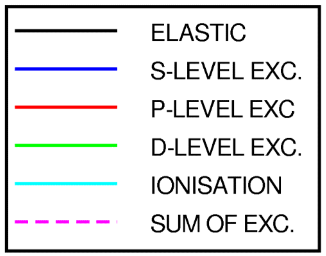


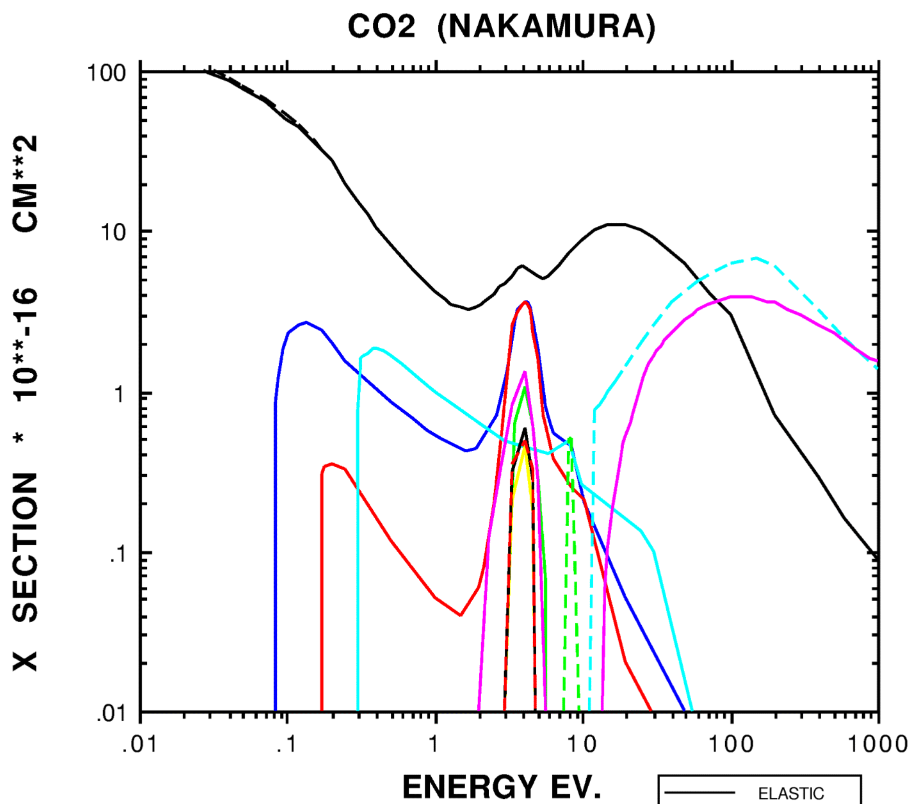
A. Peisert and F. Sauli, Drift and Diffusion of Electrons in Gases: a compilation CERN 84-08 (1984)

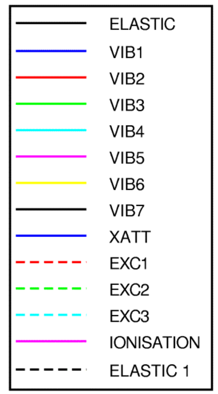
ELECTRON-MOLECULE CROSS SECTION

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









MAGBOLTZ:
Montecarlo program to compute electron drift and diffusion

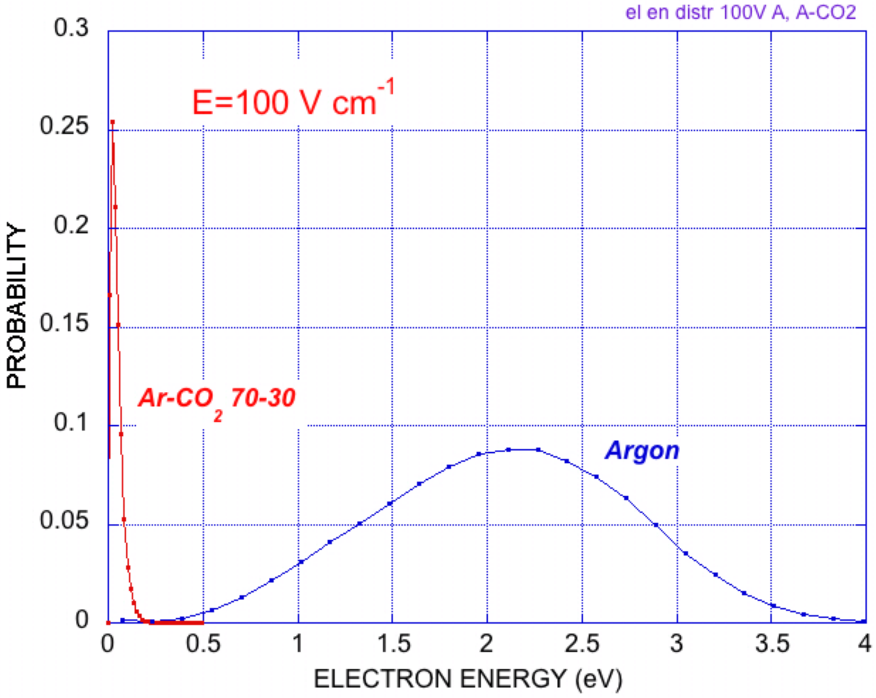
S. Biagi, Nucl. Instr. and Meth. A421(1999)234

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

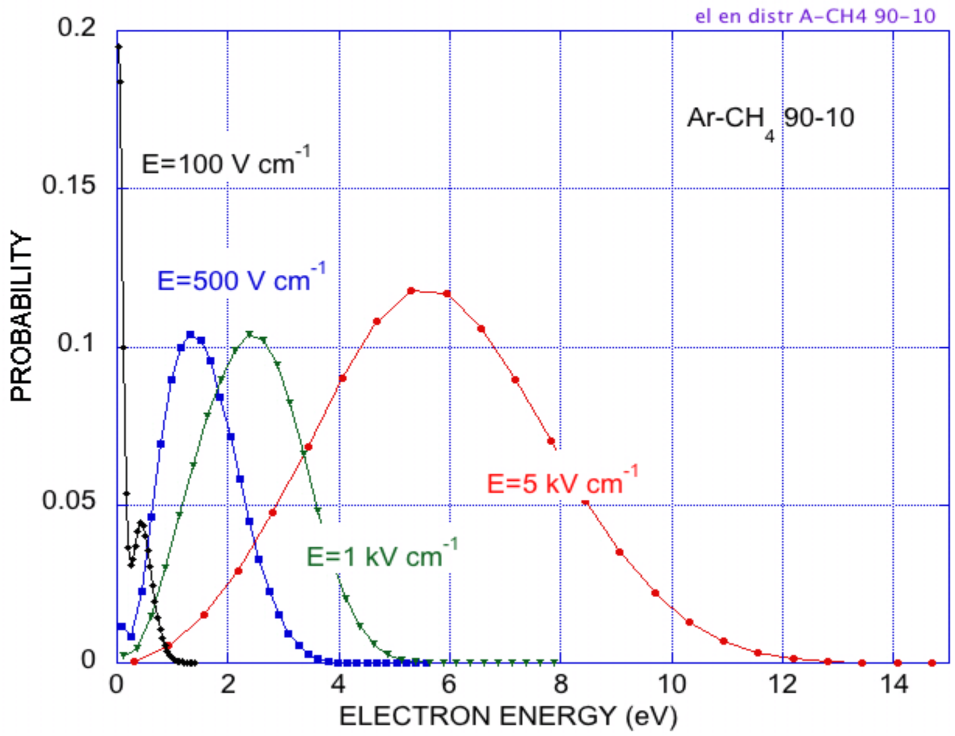
Stephen Biagi

ENERGY DISTRIBUTION AT INCREASING FIELDS:

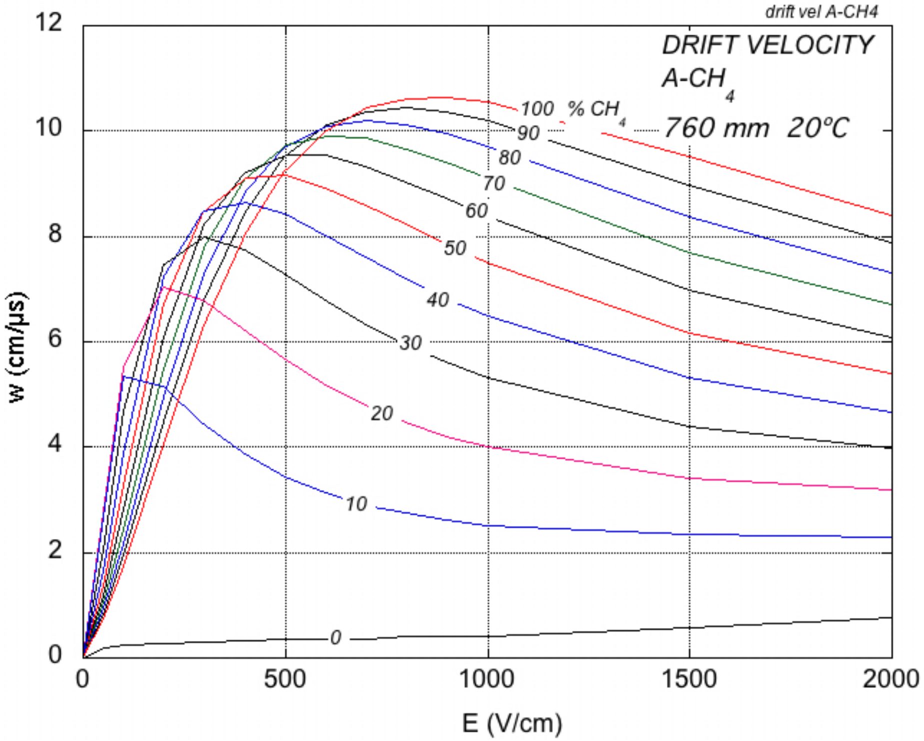
EQUAL FIELD, DIFFERENT GAS:

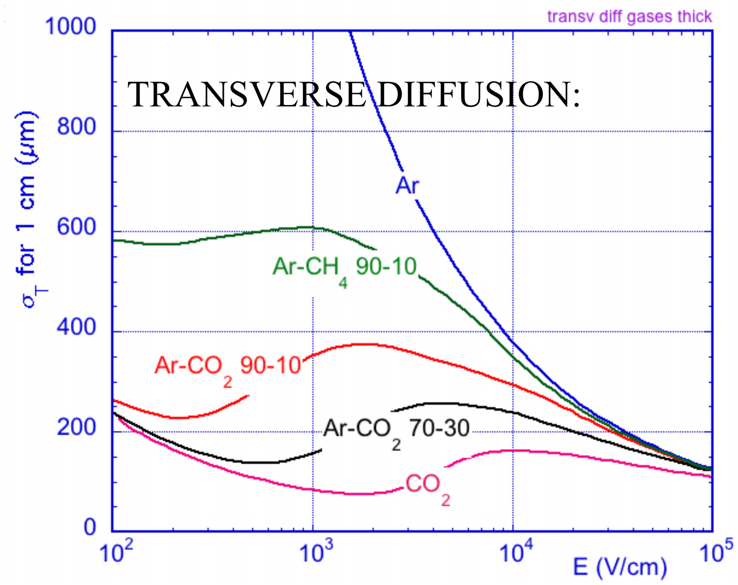


SAME GAS, INCREASING FIELD:



DRIFT VELOCITY IN ARGON-METHANE MIXTURES





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

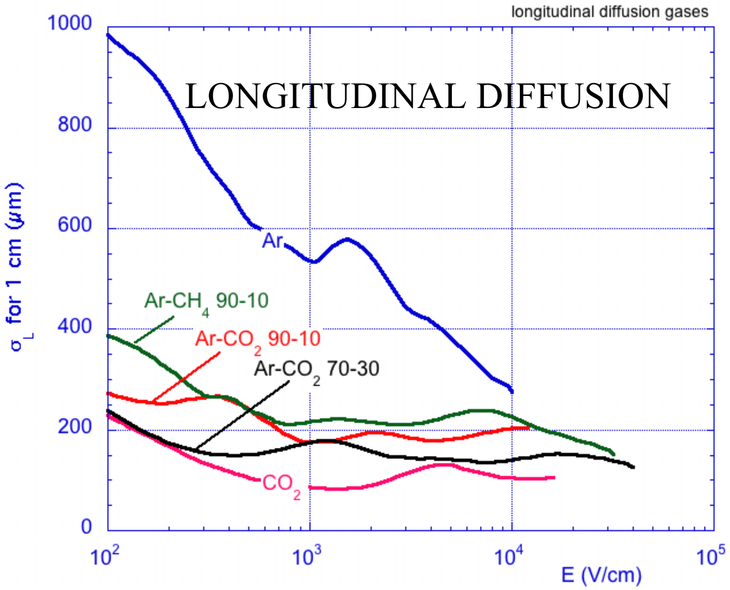
$w^- = 2.5$ cm µs^{-1}

$\sigma_T = 600$ µm

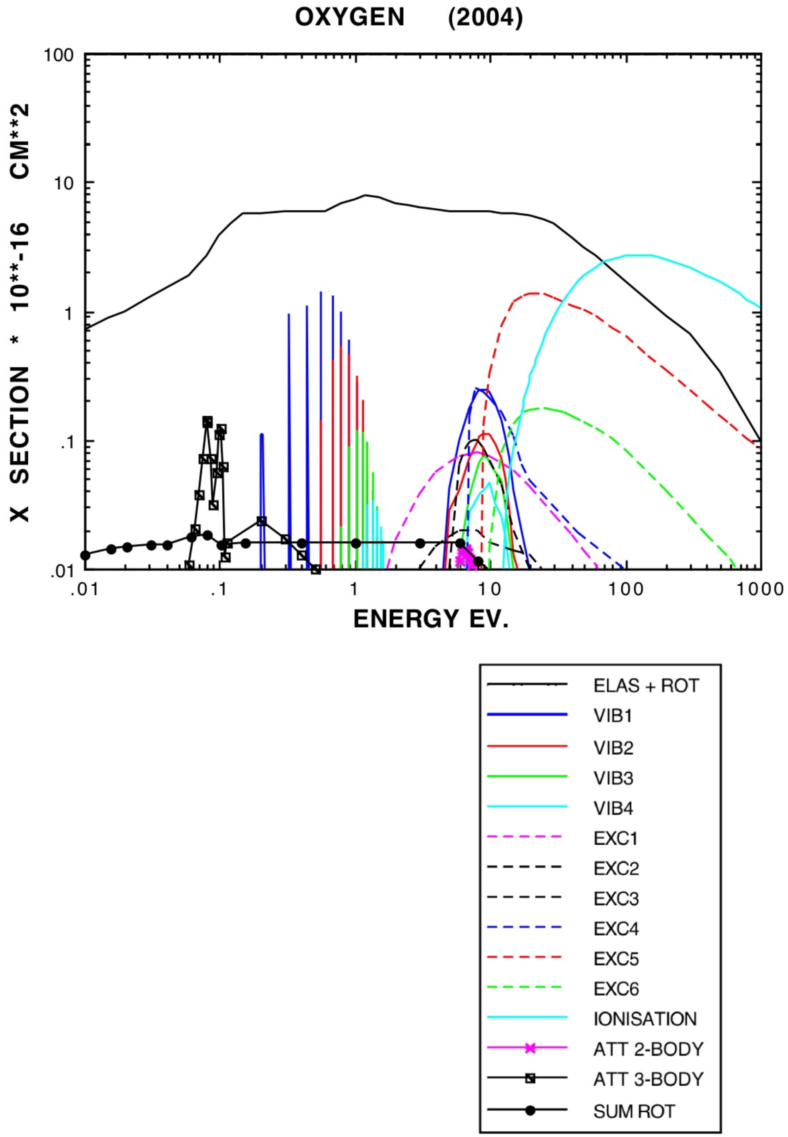
$\sigma_L = 200$ µm

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

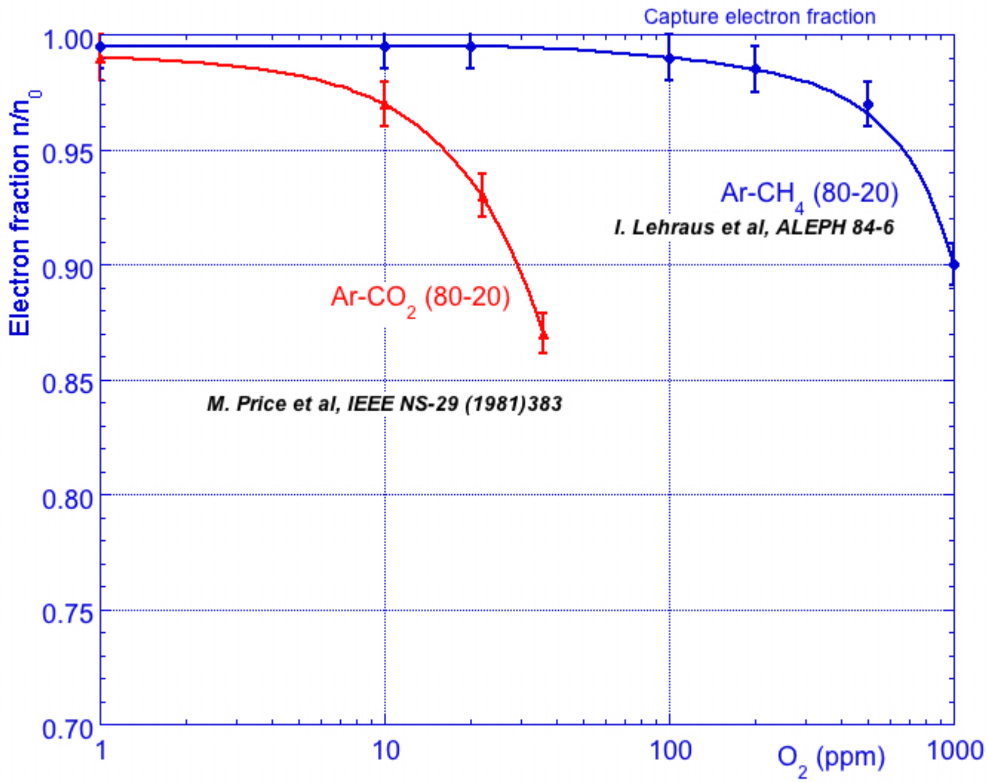
Computed with MAGBOLTZ



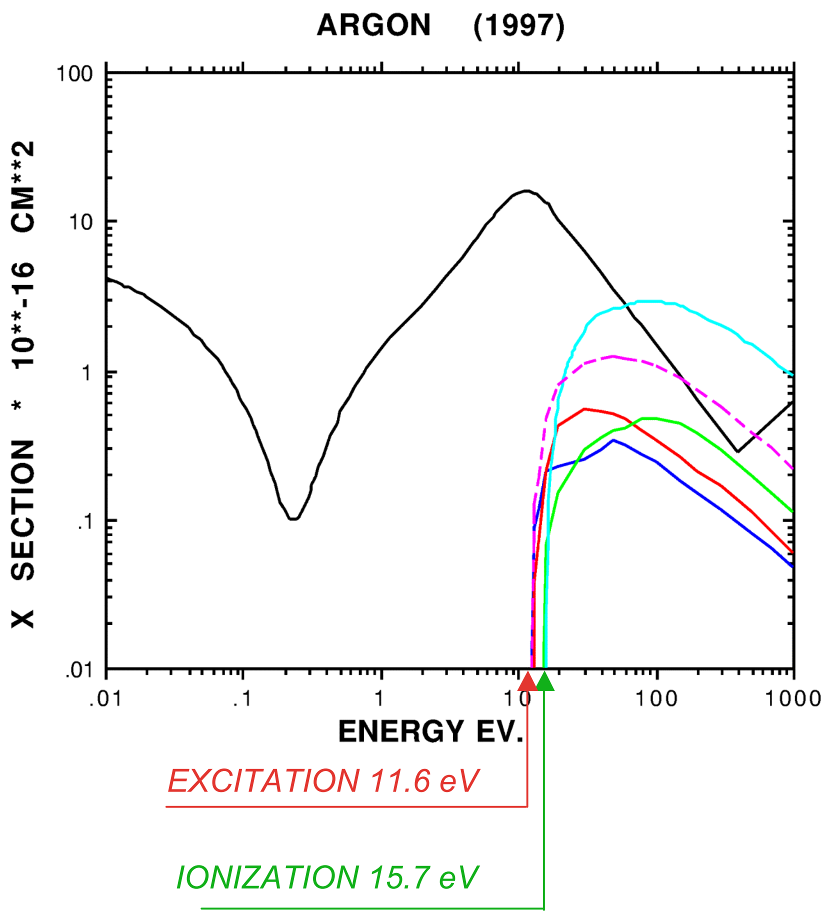
ATTACHMENT CROSS SECTION OF OXYGEN:



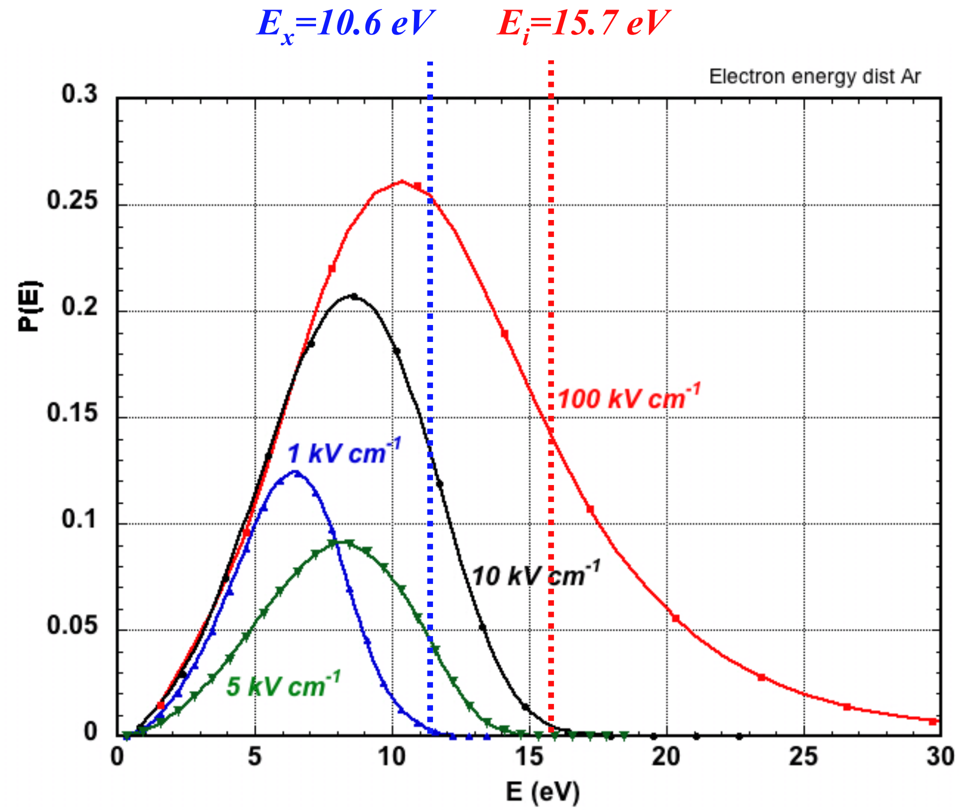
ELECTRONS SURVIVING AFTER 20 CM DRIFT (E = 200 V/cm):



ELECTRON CROSS SECTIONS IN ARGON:



ELECTRONS ENERGY DISTRIBUTION IN ARGON AT INCREASING FIELDS:



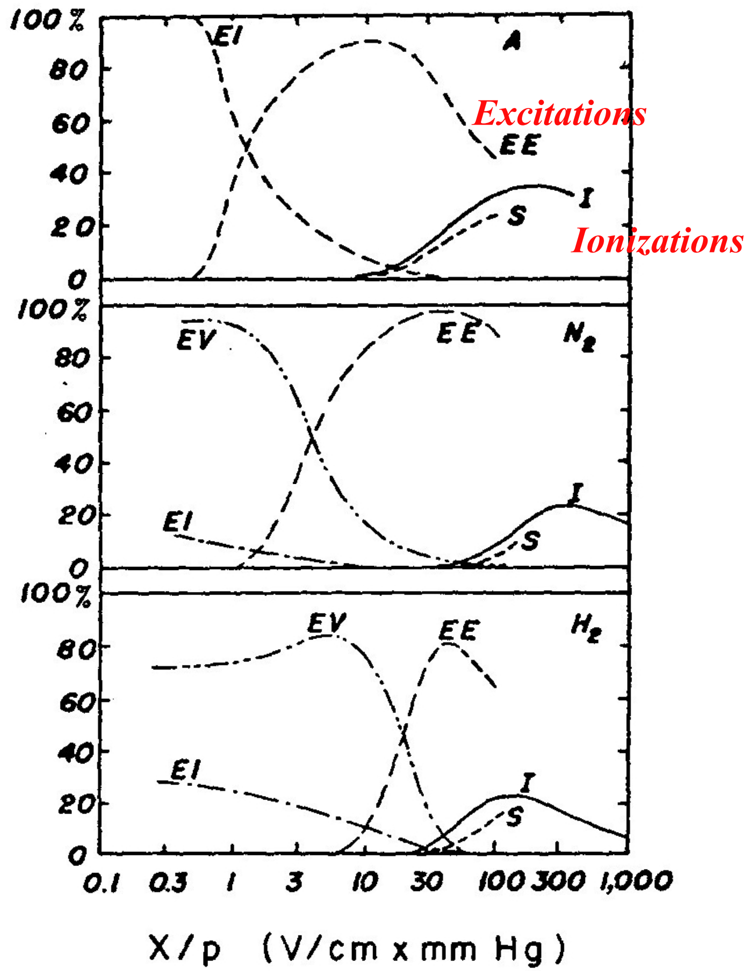
HIGH FIELD-INELASTIC COLLISIONS

MAIN ELECTRON-MOLECULE INELASTIC PROCESSES:

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

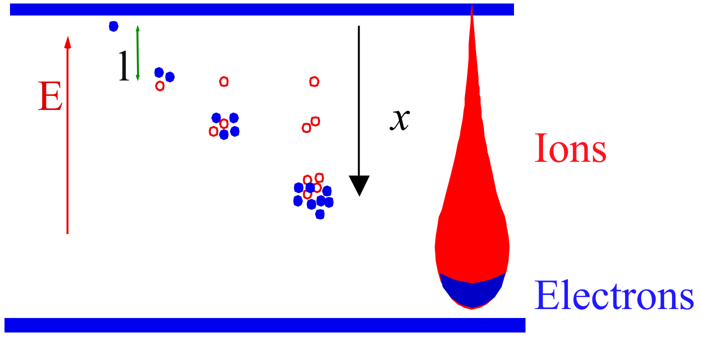
J.Meek and J. D. Cragg, Electrical Breakdown of Gases (Clarendon Press, Oxford 1953)

ENERGY SHARING BETWEEN COLLISION PROCESSES:



L. B. Loeb, Basic Processes of Gaseous Electronics (UC Berkeley Press, 1961)

CHARGE MULTIPLICATION IN UNIFORM FIELD

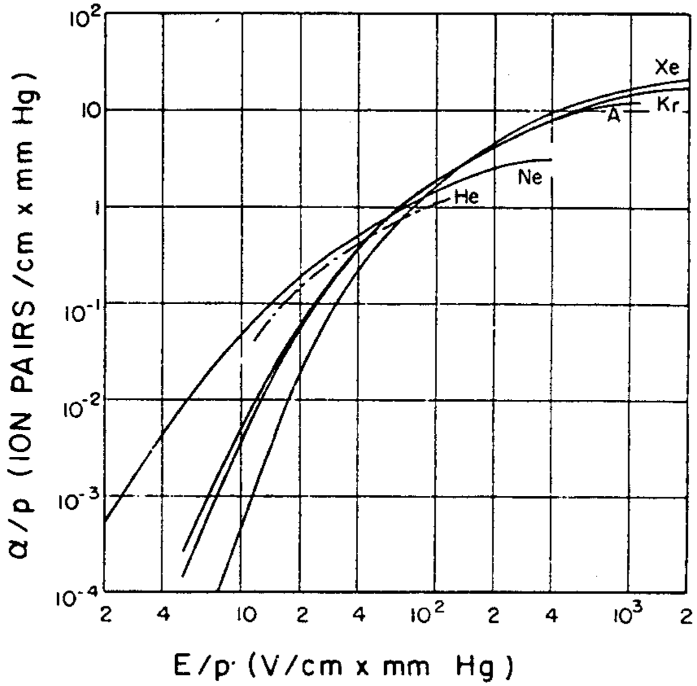


Mean free path for ionization:

$$\lambda = \frac{1}{N\sigma}$$ *N: molecules/cm³*

Townsend coefficient:

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



Incremental increase of the number of electrons in the avalanche:

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

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

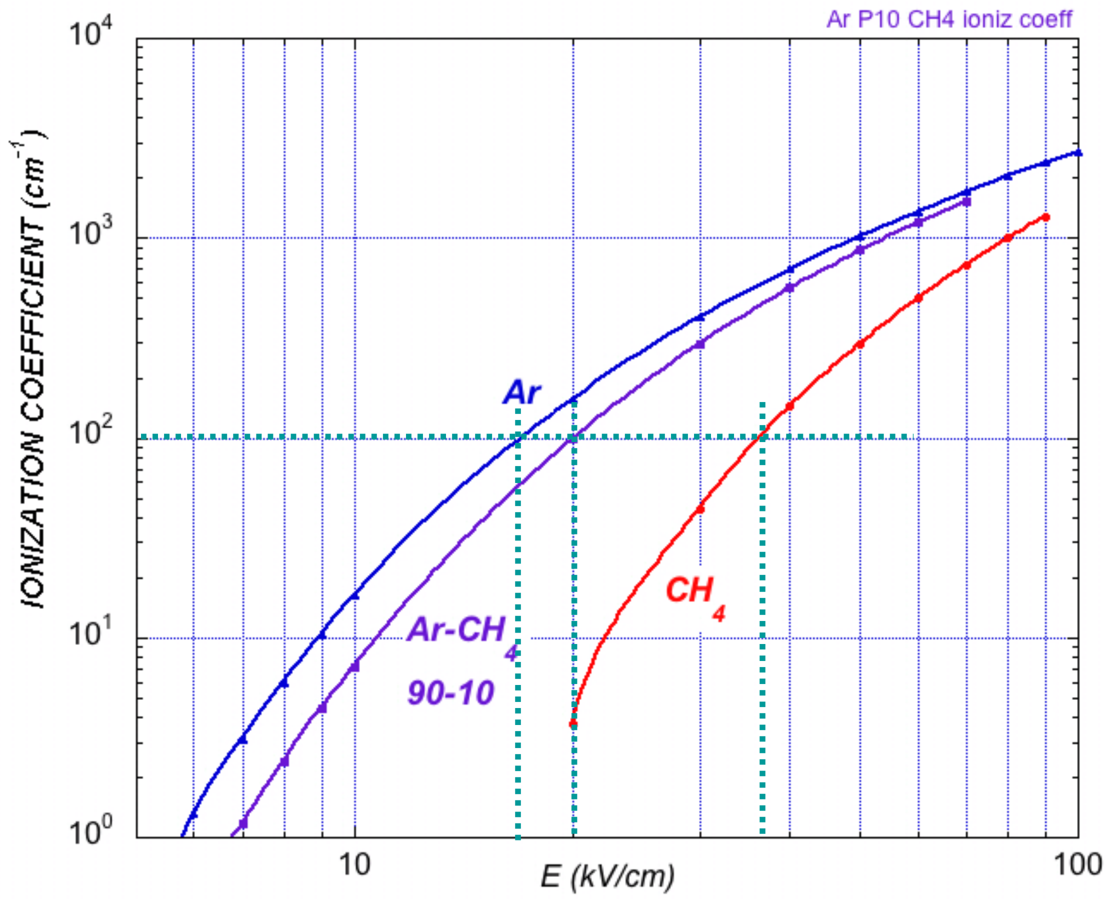
Maximum Avalanche size before discharge (Raether limit):

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

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

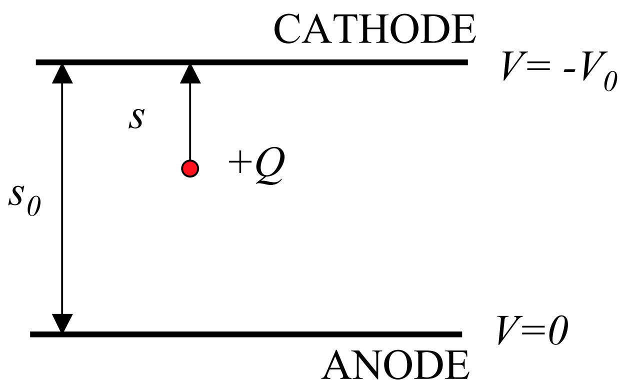
S.C. Brown, Basic Data of Plasma Physics (MIT Press, 1959)

TOWNSEND COEFFICIENT FOR Ar, CH_4 and Ar-CH_4:



(COMPUTED WITH MAGBOLTZ)

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):

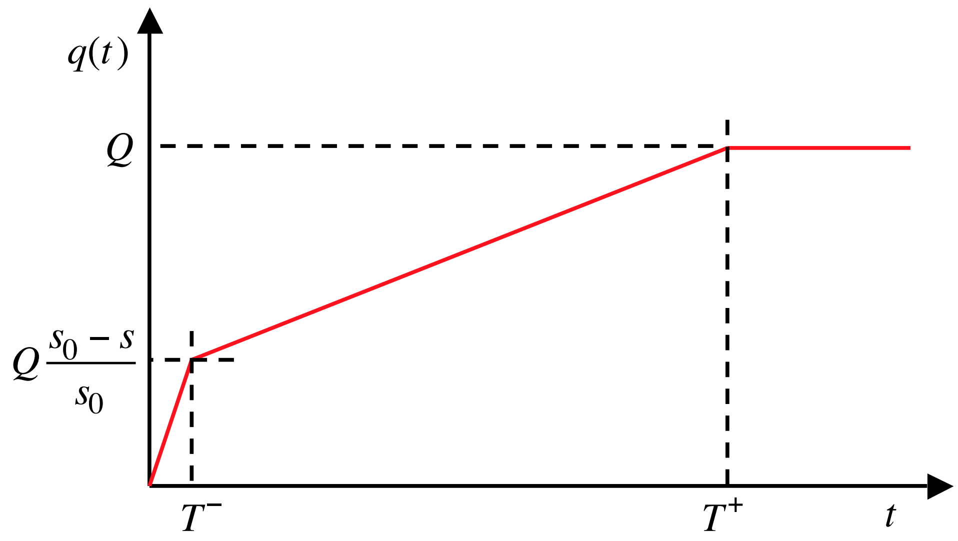
$$q(s) = \frac{Q}{s_0}s \quad q(t) = \frac{Q}{s_0}wt \quad i(t) = \frac{dq}{dt} = \frac{Q}{s_0}w$$

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

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

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

$$q(T^+) = Q$$

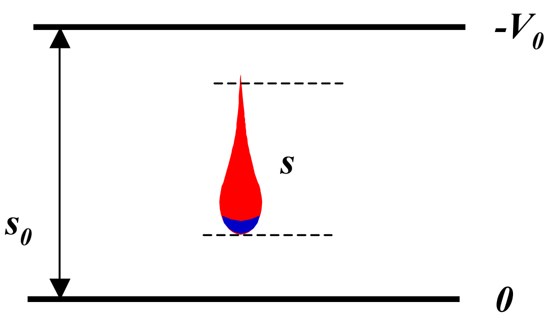


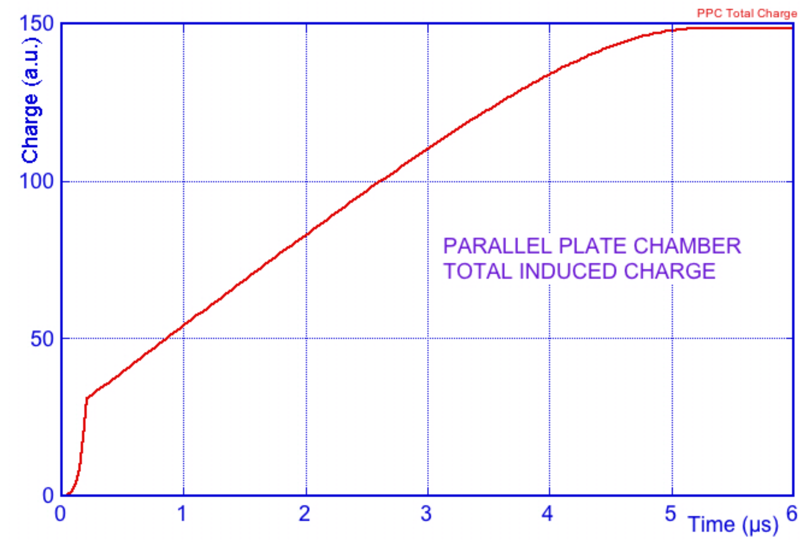
w^- (w^+) : electron (ion) drift velocity

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

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

PARALLEL PLATE COUNTERS:





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

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

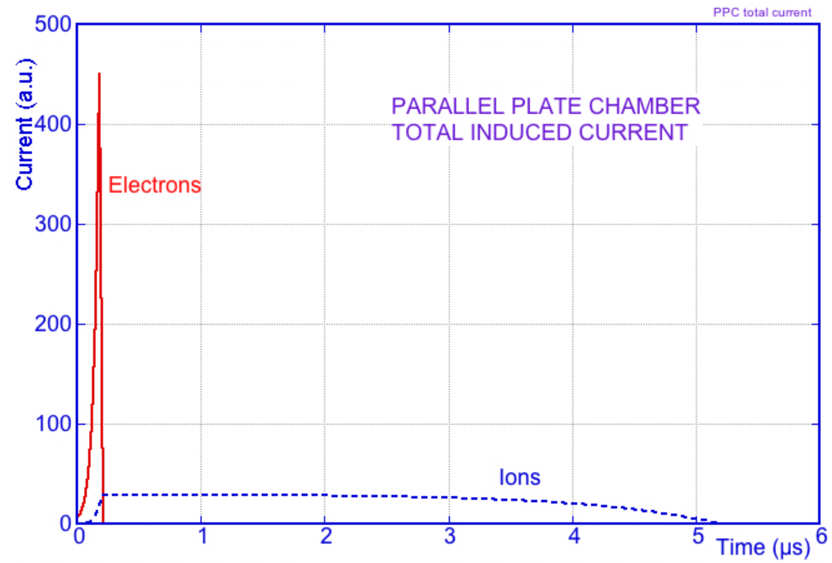
$$i^-(t) = \frac{dq^-}{dt} = \frac{en_0 w^-}{s_0}e^{\alpha w^- t} = \frac{en_0}{T^-}e^{\alpha w^- t}$$

Current signal induced by ions:

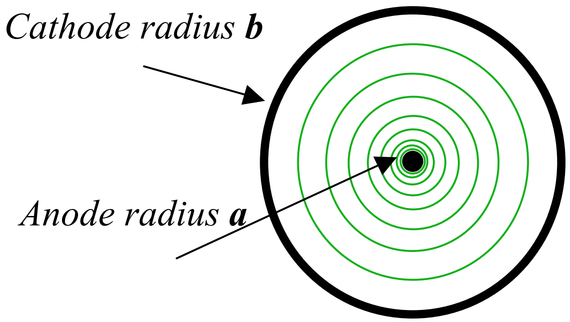
$$i^+(t) = \frac{en_0}{T^+}\left(e^{\alpha w^- t} - e^{\alpha w^* t}\right) \quad 0 \le t \le T^-$$

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

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



THIN ANODE WIRE

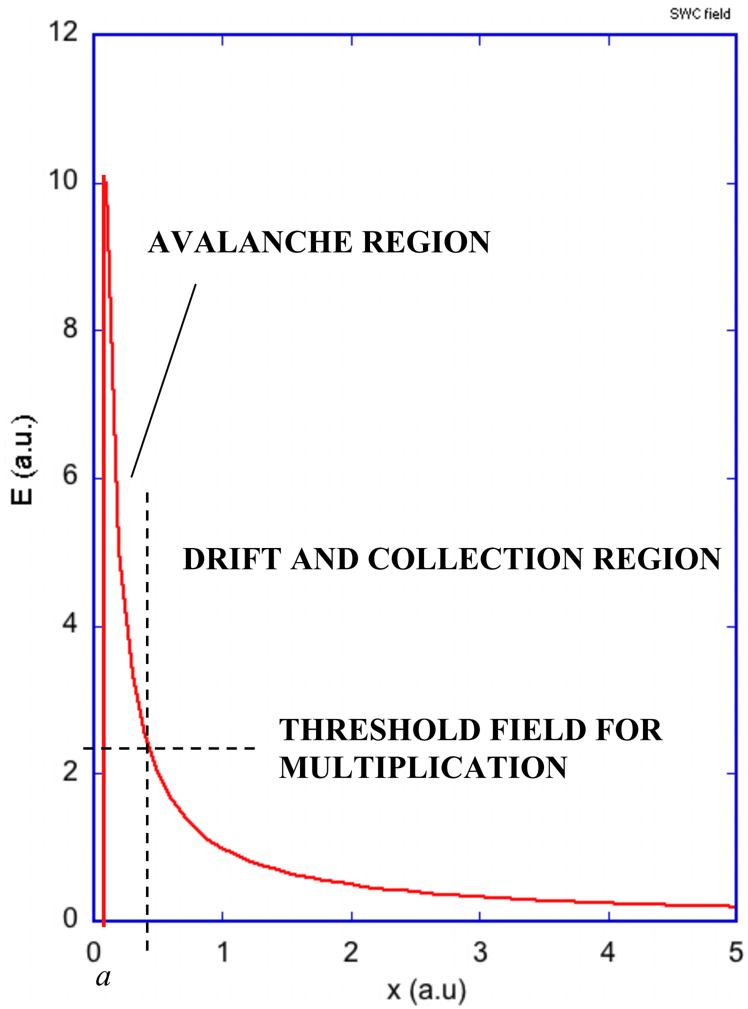


ELECTRIC FIELD AND POTENTIAL:

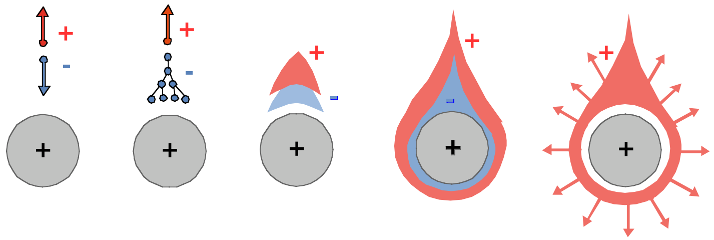
$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

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

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



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

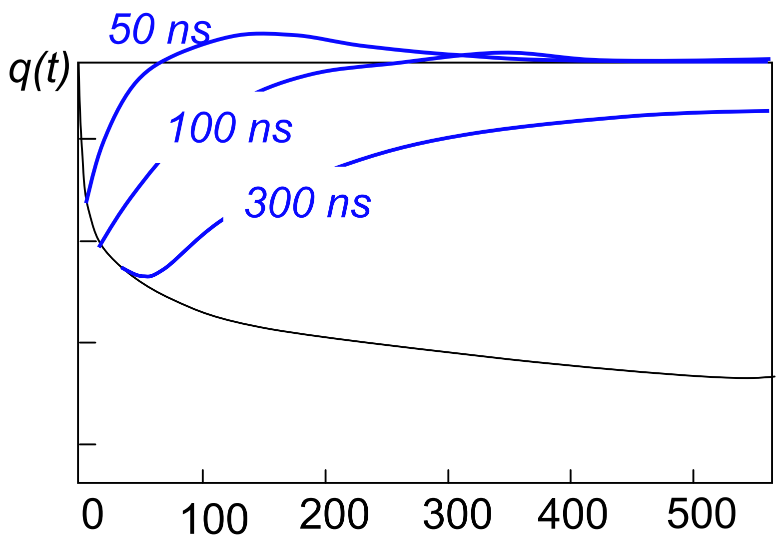
$$\frac{q^-}{q^+} = \frac{\ln(a+\lambda)-\ln a}{\ln b - \ln(a+\lambda)} \approx 0.01$$

99% of signal due to positive ions

$$q(t) = -\frac{QC}{2\pi\varepsilon_0}\ln\left(1+\frac{\mu^+ CV_0}{2\pi\varepsilon_0 a^2}t\right) = -\frac{QC}{2\pi\varepsilon_0}\ln\left(1+\frac{t}{t_0}\right)$$

CHARGE SIGNAL: POSITIVE ION TAIL

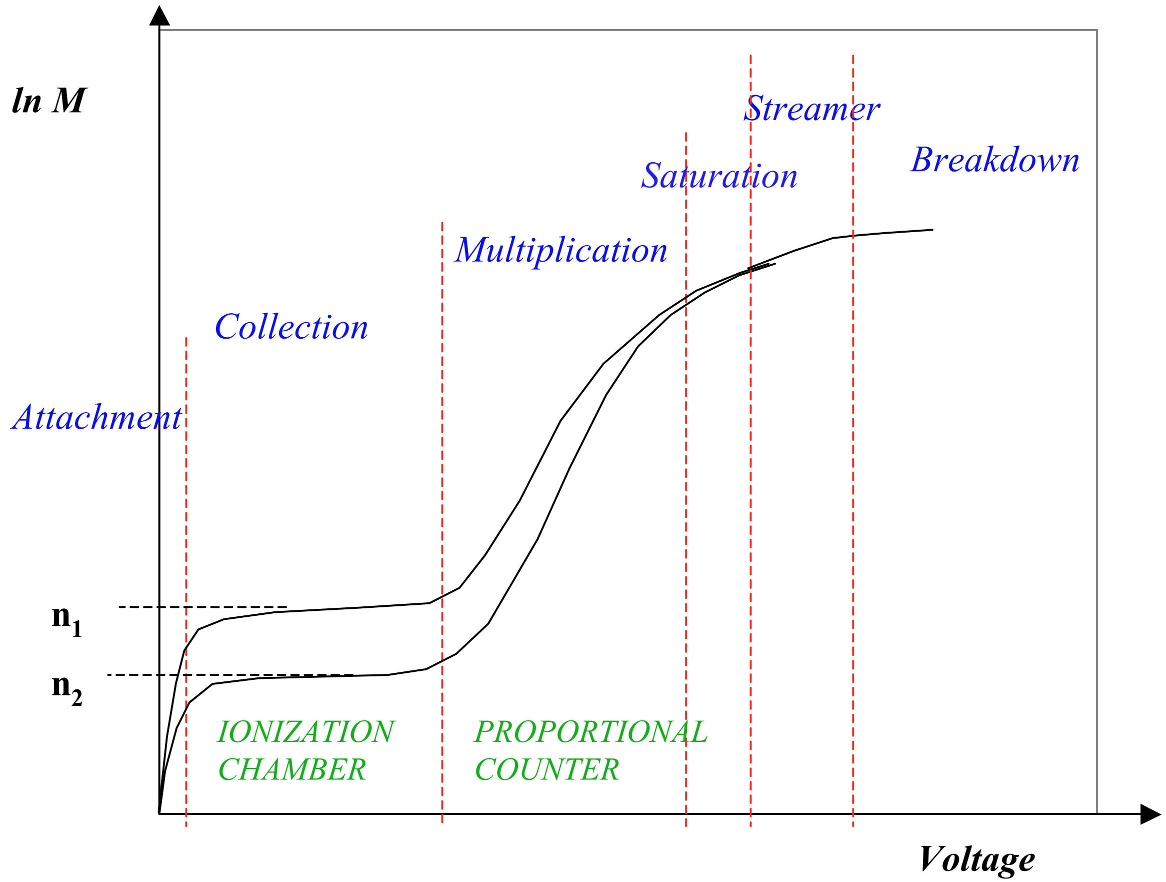
RC differentiation for faster response

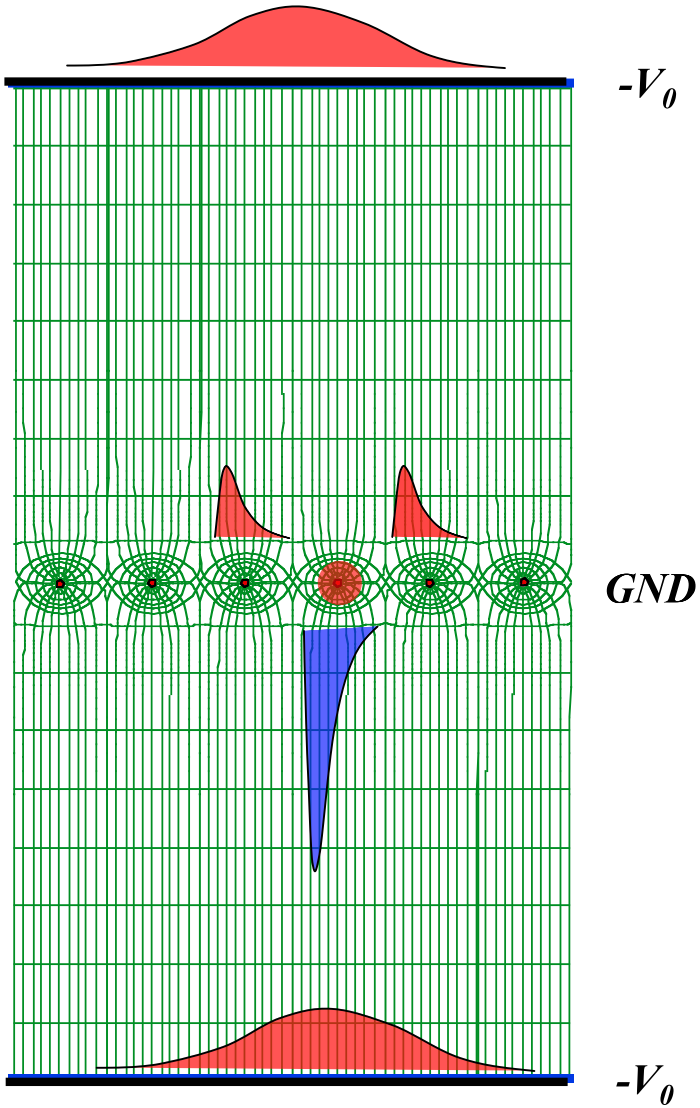


S. C. Curran and J. D. Craggs, Counting Tubes (Butterworth 1949)

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

PROPORTIONAL COUNTERS: OPERATING REGIMES

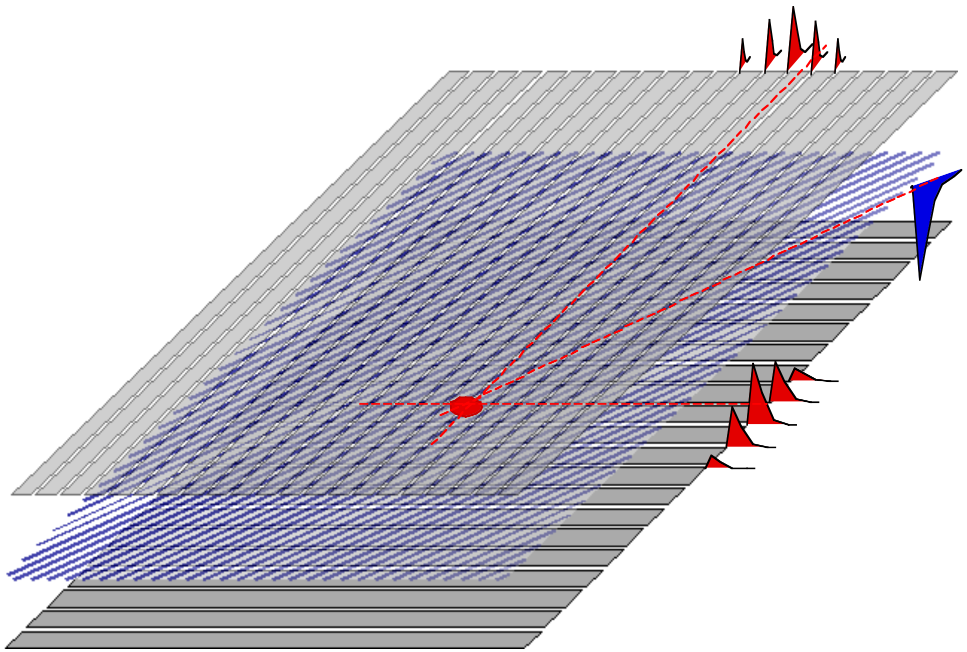




G. Charpak et al,
Nucl. Instr. and Meth. 62(1968)235

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

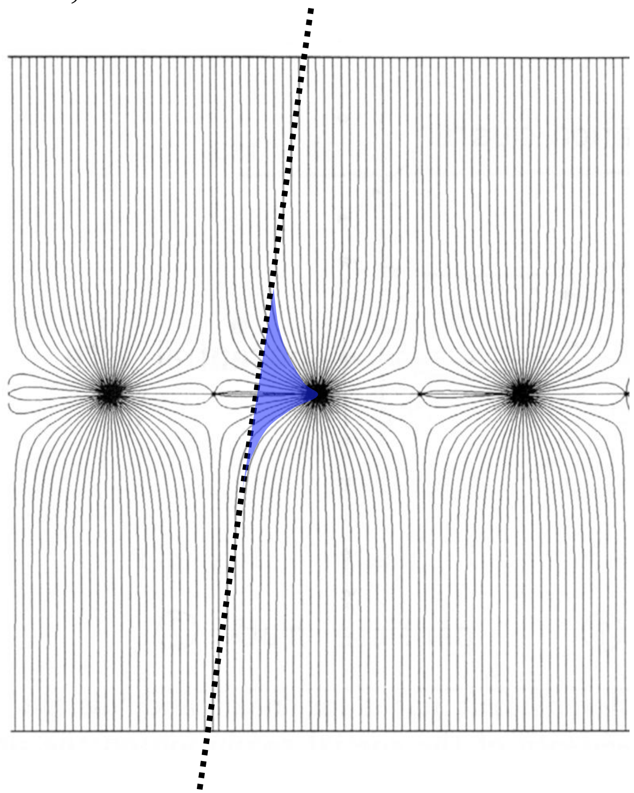
$$X = \sum \frac{X_i\, A_i(X)}{A(X)} \qquad Y = \sum \frac{Y_i\, A_i(Y)}{A(Y)}$$



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

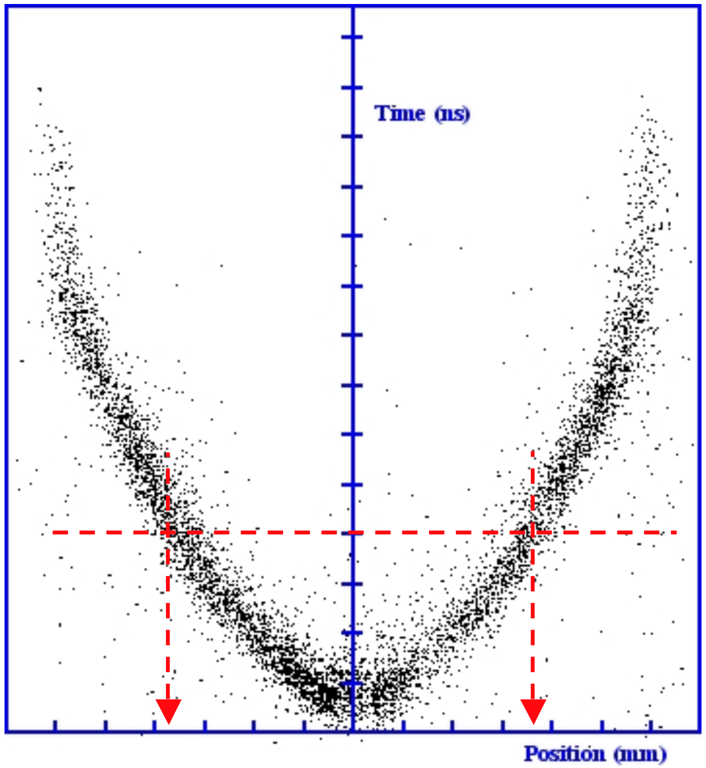
DRIFT CHAMBER

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



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

SPACE-TIME CORRELATION (RIGHT-LEFT AMBIGUITY):

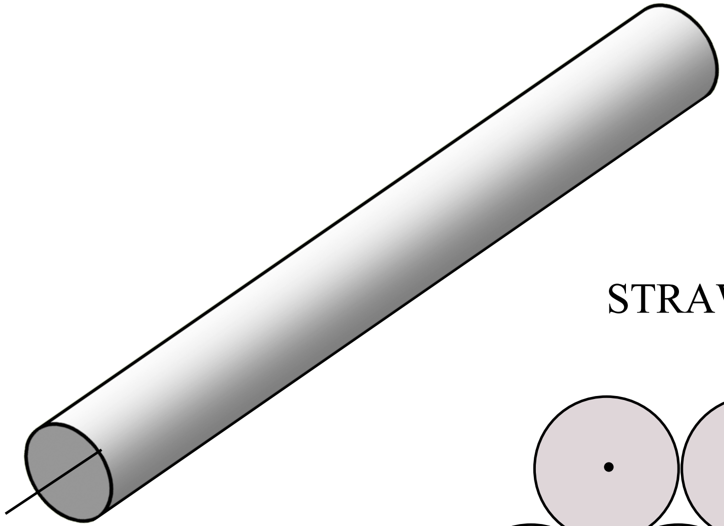


ELECTRIC FIELD AND DRIFT PROPERTIES CALCULATIONS: GARFIELD

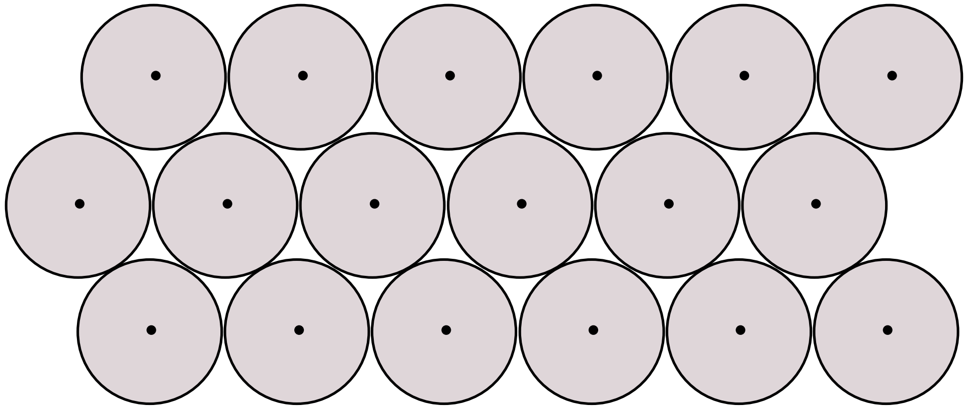
Rob Veenhof

LABORATORY: STRAWS AND DRIFT TUBES

SINGLE WIRE PROPORTIONAL COUNTERS

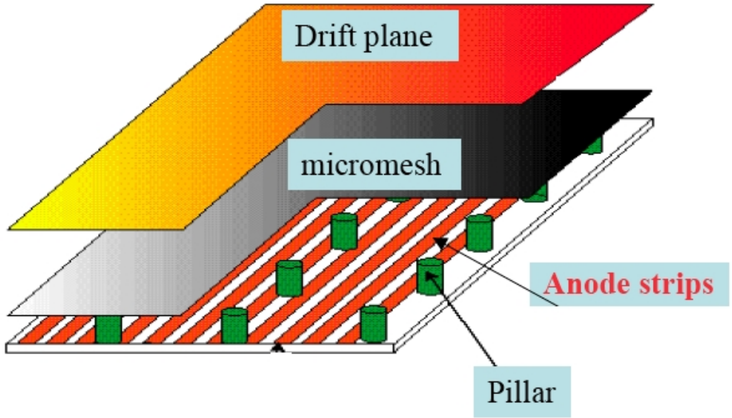


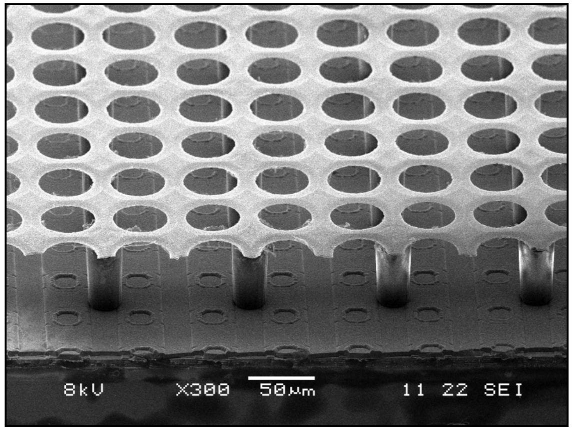
STRAWS ARRAYS:



Anatoli Romaniouk: ATLAS Transition Radiation Tracker (TRT)
Hans Danielsson: NA62 Straw Detectors
Joerg Dubbert: ATLAS Monitored Drift Tubes (MDT)

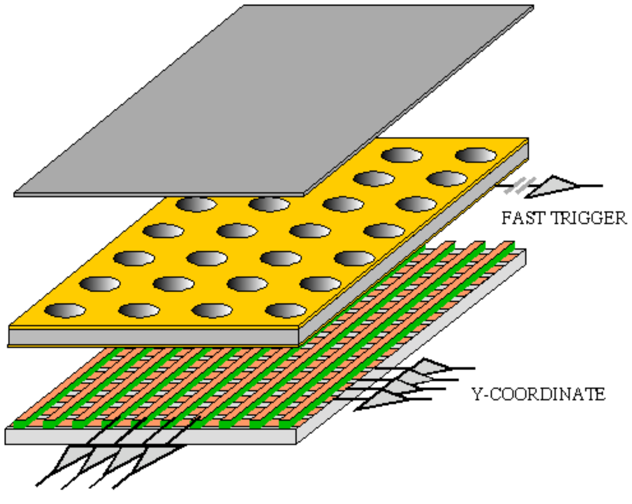
MICROMEGAS and GRIDPIX

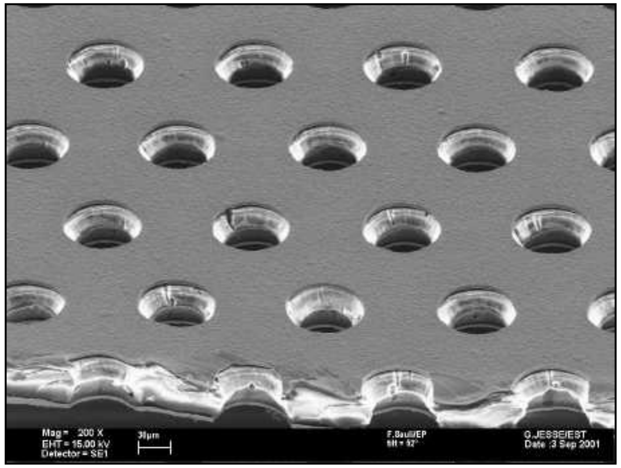




Paul Colas
Harry van der Graaf

GAS ELECTRON MULTIPLIER (GEM)





Gianni Bencivenni

AND NOW, PUT YOUR HANDS ON (CAREFULLY)!

THE END