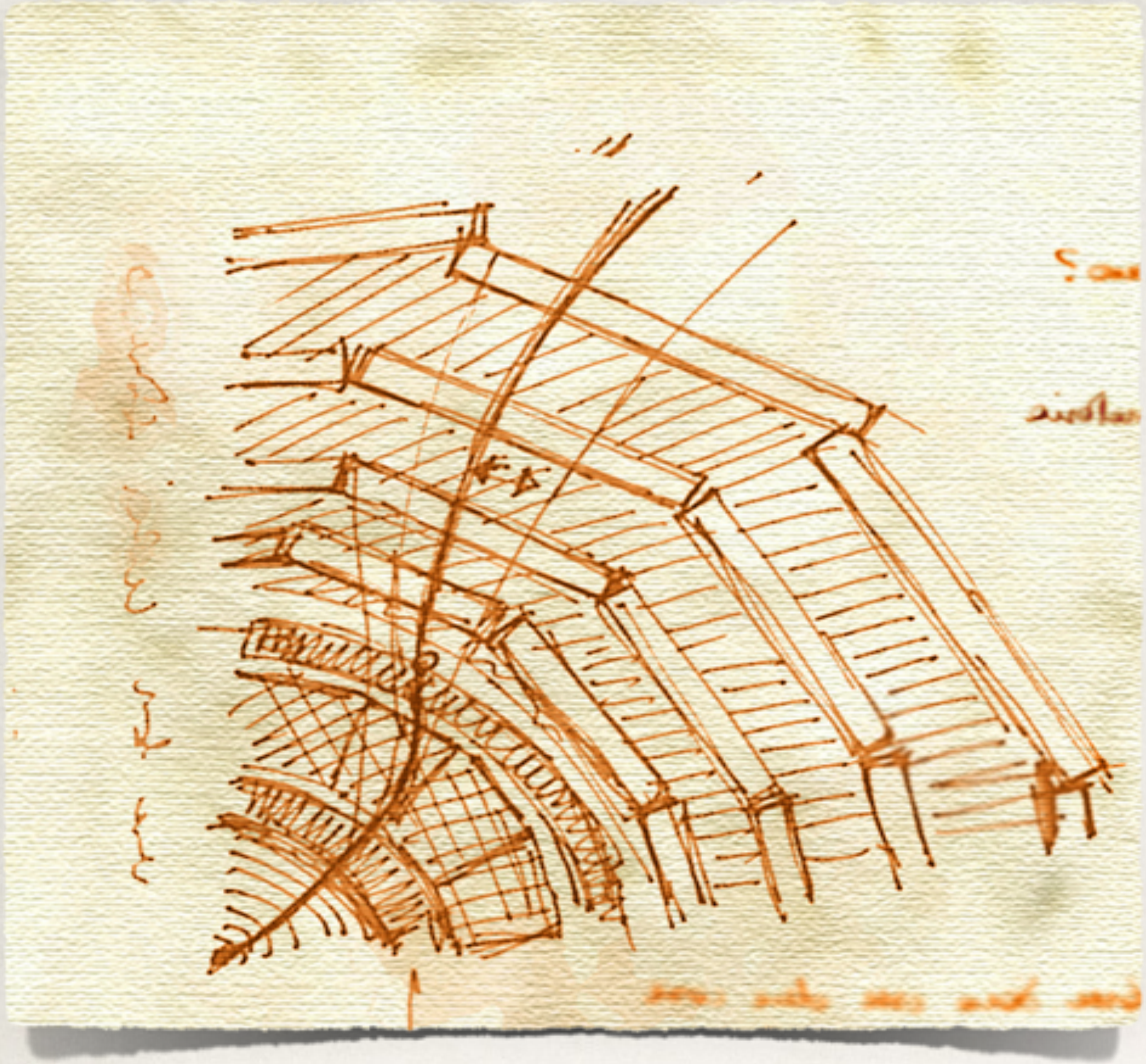

XI Escola do CBPF

Curso de Pós-Graduação

Notas de Aula

A Física dos Detectores de Partículas

Dr Arthur M. Moraes - CBPF

(web-page: http://cern.ch/amoraes)

25 de Julho de 2017

CBPF
Centro Brasileiro de Pesquisas Físicas

Introdução

Programa do Curso:

Aula 1: De Rutherford ao LHC: Desenvolvimento dos detectores ao longo da história da física das partículas elementares. (2ªf. 17/07)

Aula 2: Interações das partículas com a matéria. (3ªf. 18/07)

Aula 3: Detectando partículas carregadas & neutras. (5ªf. 20/07)

Aula 4: Cintiladores: detectando partículas via luminescência. (6ªf. 21/07)

Aula 5: Detectores de semicondutores: medidas de alta precisão. (2ªf. 24/07)

Aula 6: Detectores de gás: medindo partículas em grandes volumes. (3ªf. 25/07)

Aula 7: Calorímetros: eletromagnéticos & hadrônicos. (5ªf. 27/07)

Aula 8: Exemplos de aplicações dos detectores em várias áreas. (6ªf. 28/07)

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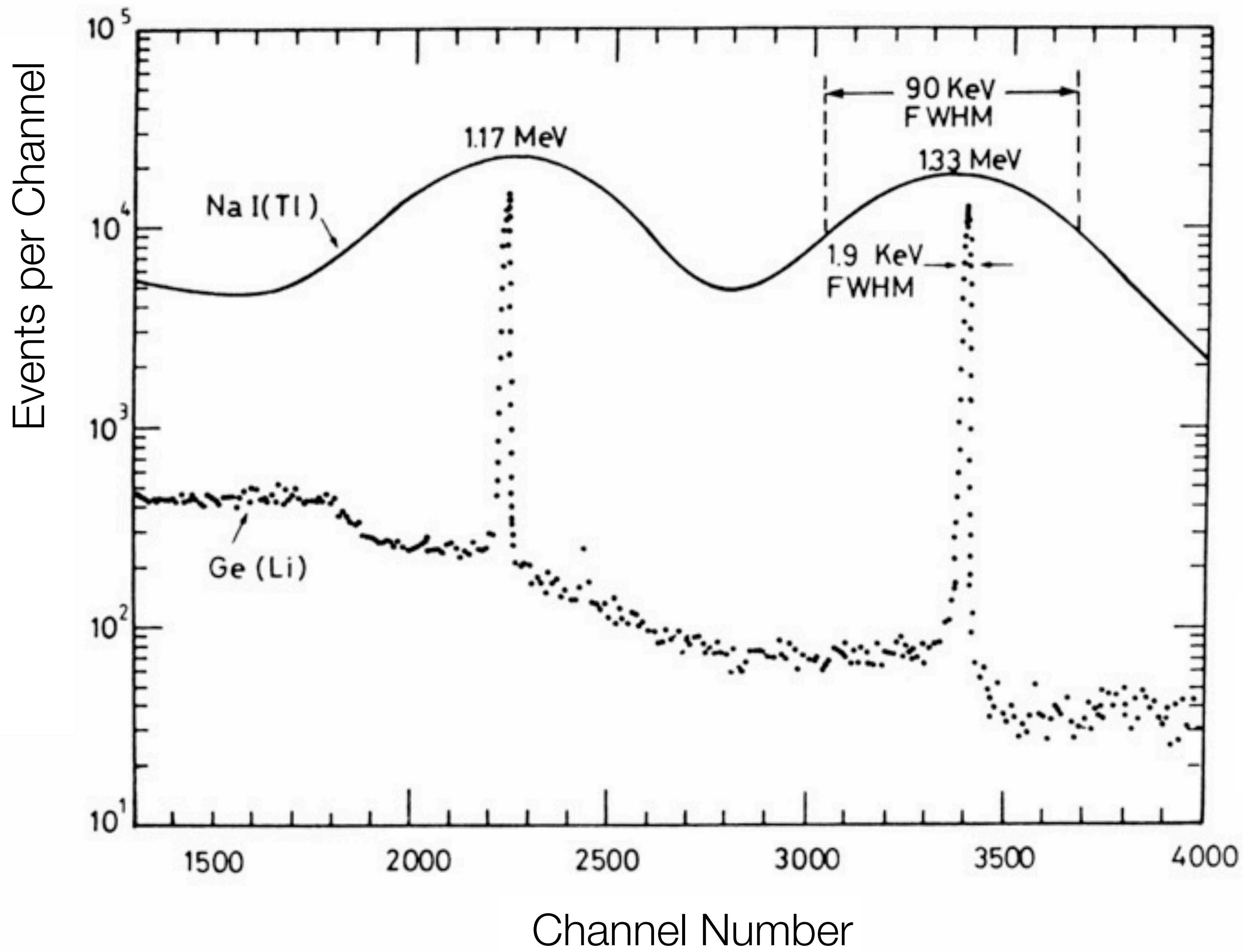
Cintilador vs Semicondutor



Comparison
of two ^{60}Co γ-spectra
one measured with NaI(Tl)
and With Ge(Li) Detector

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Aula 6

Detectores de gás: medindo partículas em grandes volumes

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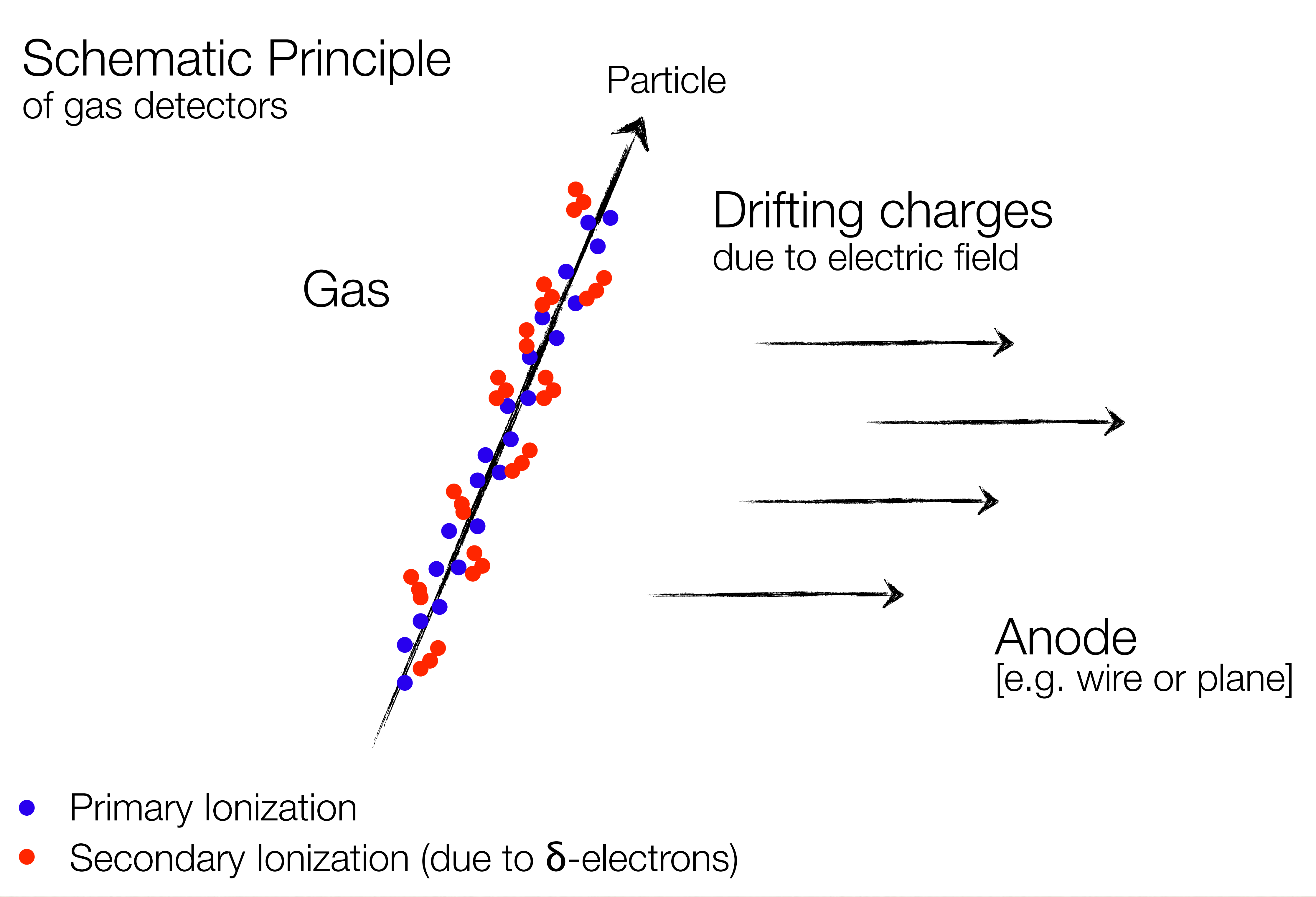
Detectores de gás



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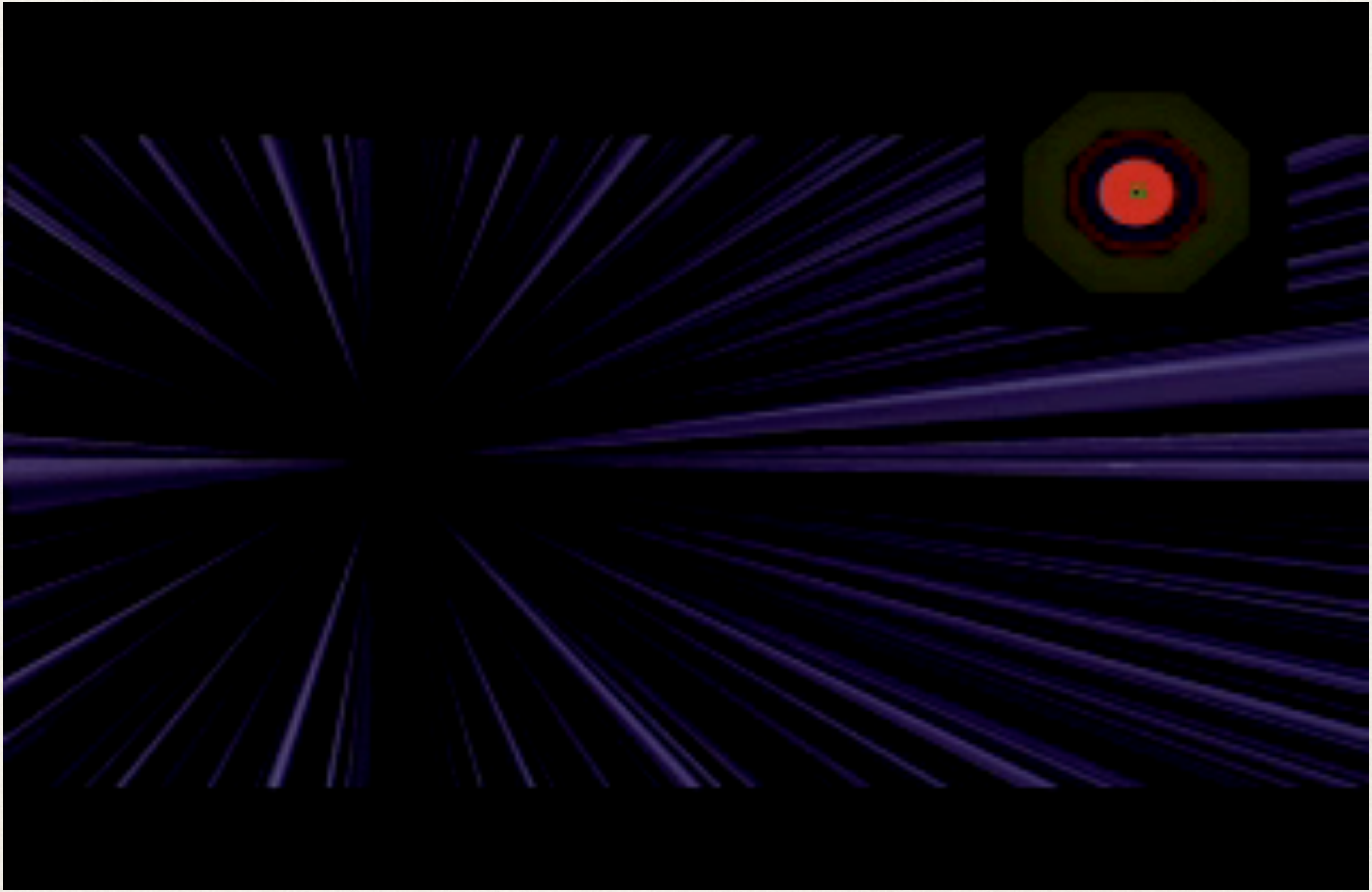
Detectores de gás



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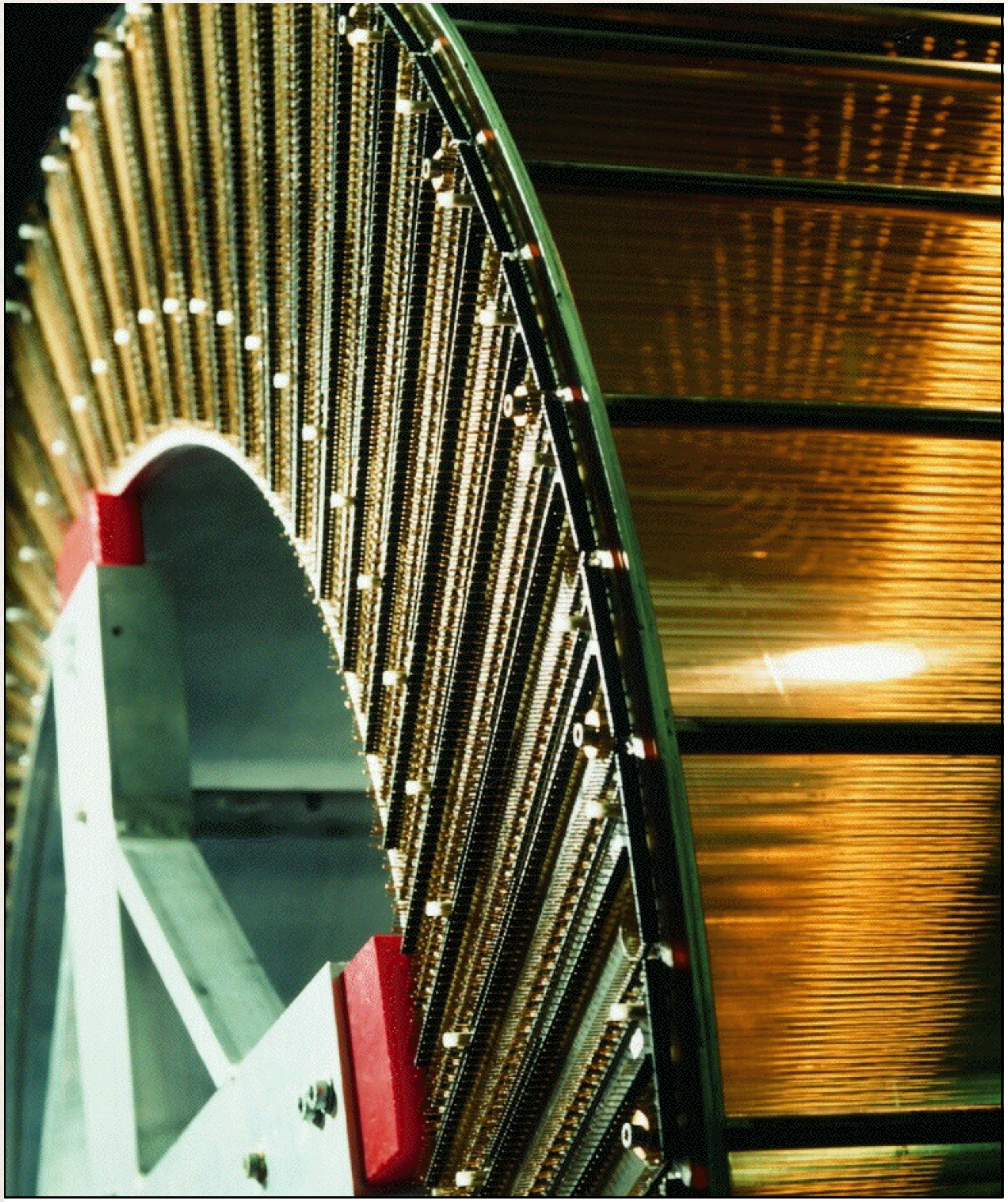
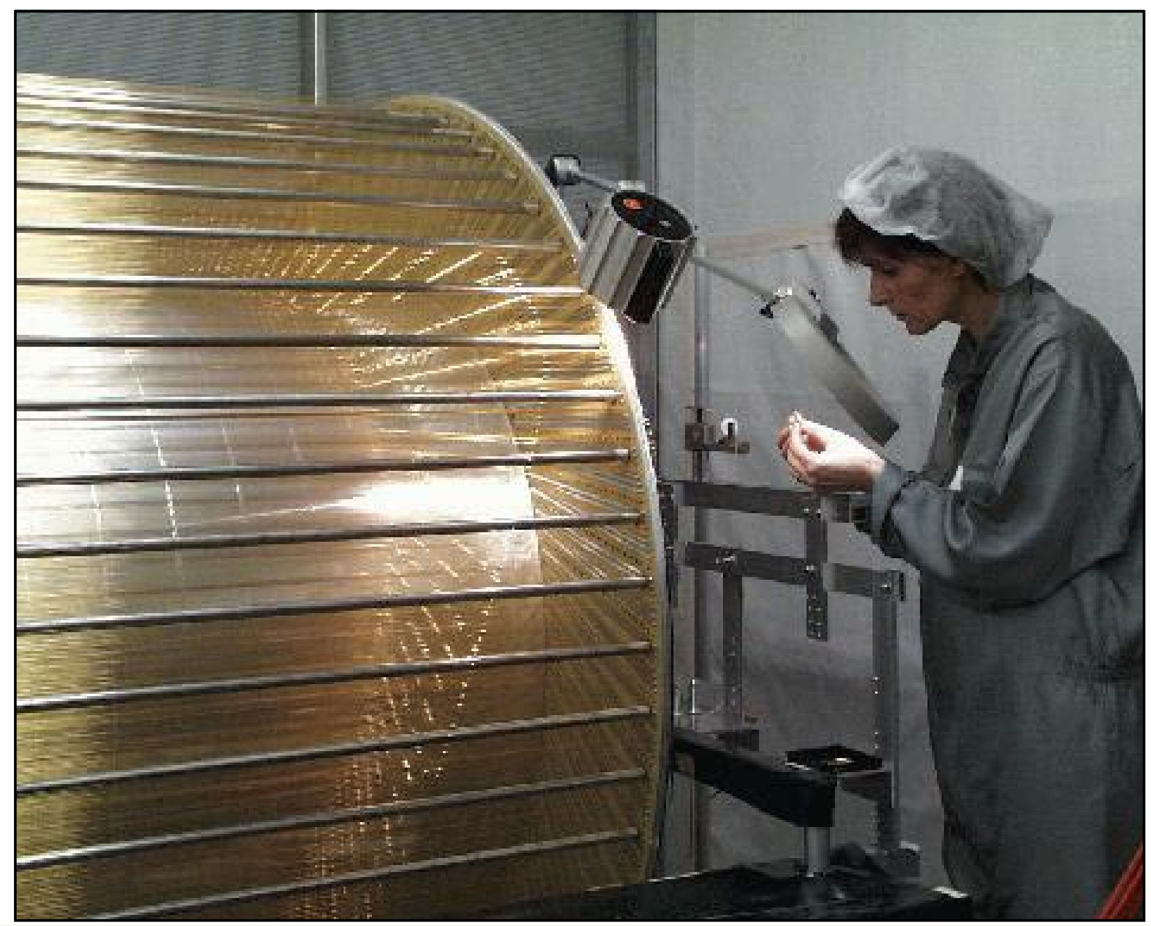
Detectores de gás



Cylindrical
Drift Chamber

[H1 Experiment]

Number of wires: ~ 15000
Total force from wire tension: ~ 6 t



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Detectores de gás

ALICE TPC *(Time Projection Chamber)*

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Detectores de gás

Relevant Parameters
for gas detectors

Ionization energy	:	E_i
Average energy/ion pair	:	W_i
Average number of primary ion pairs [per cm]	:	n_p
Average number of ion pairs [per cm]	:	n_T

Differences due to δ-electrons

$$\langle n_T \rangle = \frac{L \cdot \left\langle \frac{dE}{dx} \right\rangle_{\mathrm{i}}}{W_i}$$

[about 2-6 times n_p]
[L: layer thickness]

δ-electrons lead to secondary ionization and limit spatial resolution; typical length scale of secondary ionization: 10 μm. Example: kinetic energy: T_{kin} = 1 keV; gas: Isobutane ➛ range: R = 20 μm ...
[using R [g/cm^2] = 0.71 $(T_{kin})^{1.72}$ [MeV]; valid for T_{kin} < 100 keV]

Gas	<Z>	ρ [g/cm^3]	E_i [eV]	W_i [eV]	dE/dx [keV/cm]	n_p [cm^{-1}]	n_T [cm^{-1}]
He	2	$1.66\cdot10^{-4}$	24.6	41	0.32	5.9	7.8
Ar	18	$1.66\cdot10^{-3}$	15.8	27	2.44	29.4	94
CH_4	19	$6.7\cdot10^{-4}$	13.1	28	1.48	18	53
C_4H_{10}	34	$2.42\cdot10^{-3}$	10.6	23	4.50	46	195

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Detectores de gás

Ionization statistics:

Mean free path λ:
[typical values]

He	0.25 cm
Air	0.052 cm
Xe	0.023 cm

[➛ σ_I(He) ≈ 100 b]

Mean distance between two ionizations: $\lambda = 1/(n_e \sigma_I)$

Mean number of ionizations: $\langle n_p \rangle = L/\lambda$

σ_I : Ionization x-Section
n_e : Electron density
L : Thickness

n_p Poissonian distributed:

$$P(n_p, \langle n_p \rangle) = \frac{\langle n_p \rangle^{n_p} e^{-\langle n_p \rangle}}{n_p!}$$

P(0) = exp(-L/λ) yields λ, σ_I
using (in)efficiency of gas-detectors

Also important:

Mobility of charges:
Influences the timing behavior of gas detectors ...

Diffusion:
Influences the spatial resolution ...

Avalanche process via impact ionization:
Important for the gain factor of the gas detector ...

Recombination and electron attachment:
Admixture of electronegative gases (O_2, F, Cl ...) influences detection efficiency ...

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Deslocamento e difusão no gás

Ion mobility:

With external electric field: ions obtain velocity v_D in addition to thermal motion; on average ions move along field lines of electric field E ...

Kinetic energy:

Temperature sorry ...

$$\langle T_{\text{ion}}(\text{E} \neq 0) \rangle \;=\; \langle T_{\text{ion}}(\text{Therm.}) \rangle \;=\; \frac{3}{2} kT$$

approximately equal to thermal energy, as the (heavy) ions loose typically half their energy when colliding with the non-ionized gas atoms.

Drift velocity v_D develops only from one interaction to another ...
Assuming $v_D(t=0) = 0$ and collision time **τ** yields:

$$\vec{v} = \vec{a} \cdot \tau = \frac{e\vec{E}}{M} \cdot \tau$$

$$\vec{v}_D = \langle \vec{v} \rangle = \frac{1}{2}\vec{v} = \frac{e|\vec{E}|}{2M} \cdot \tau = \mu_+ |\vec{E}|$$

$$\tau = \lambda(T_{\text{kin}})/v_{\text{therm.}} = \text{const.}$$

since T_{kin} essentially thermal, and $v_{therm.}$ thus constant ...

Drift velocity v_D for ions proportional to E !

μ_+ : ion mobility   e.g. $\mu_+ = 0.61\ \text{cm}^2/\text{Vs}$ for C_4H_{10}

[E = 1 kV/cm; typical drift distances = few cm ➛ typical ion drift time = few ms]

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Deslocamento e difusão no gás

Electron mobility: $\vec{v}_D = \mu\vec{E}$
[B = 0]

Compare:
Electrons: v_D of order cm/μs
Ions: v_D of order cm/ms

Consider two situations:

$T_{kin,e}$ » kT — gas atoms have only a few low-lying energy levels such that electrons can lose little energy in collisions [hot gases]

$\lambda(T_e) \sim \lambda(E)$ and $\mu \sim \tau \sim 1/\sigma(E)$

μ not constant!
[If λ ~ 1/E; v_D = const]

Electrons accelerated in E-field until sufficient energy is reached ...
Higher E-field yields smaller mean free path ➛ constant v_D possible ...
[Example: v_D = 3 – 5 cm/μs for 90% Ar/10% CH_4]

$T_{kin,e} \approx$ kT — gas atoms have many low-lying energy levels such that electrons loose all energy they gain between collisions [cold gases]

$\mu \approx \text{const.}$ and $v_D \propto E$

Similar to situation with ions ...
[Example: μ = $7 \cdot 10^{-3}$ cm^2/μs V for 90% Ne/10% CO_2; v_D = 2 cm/μs @ 300 V/cm]

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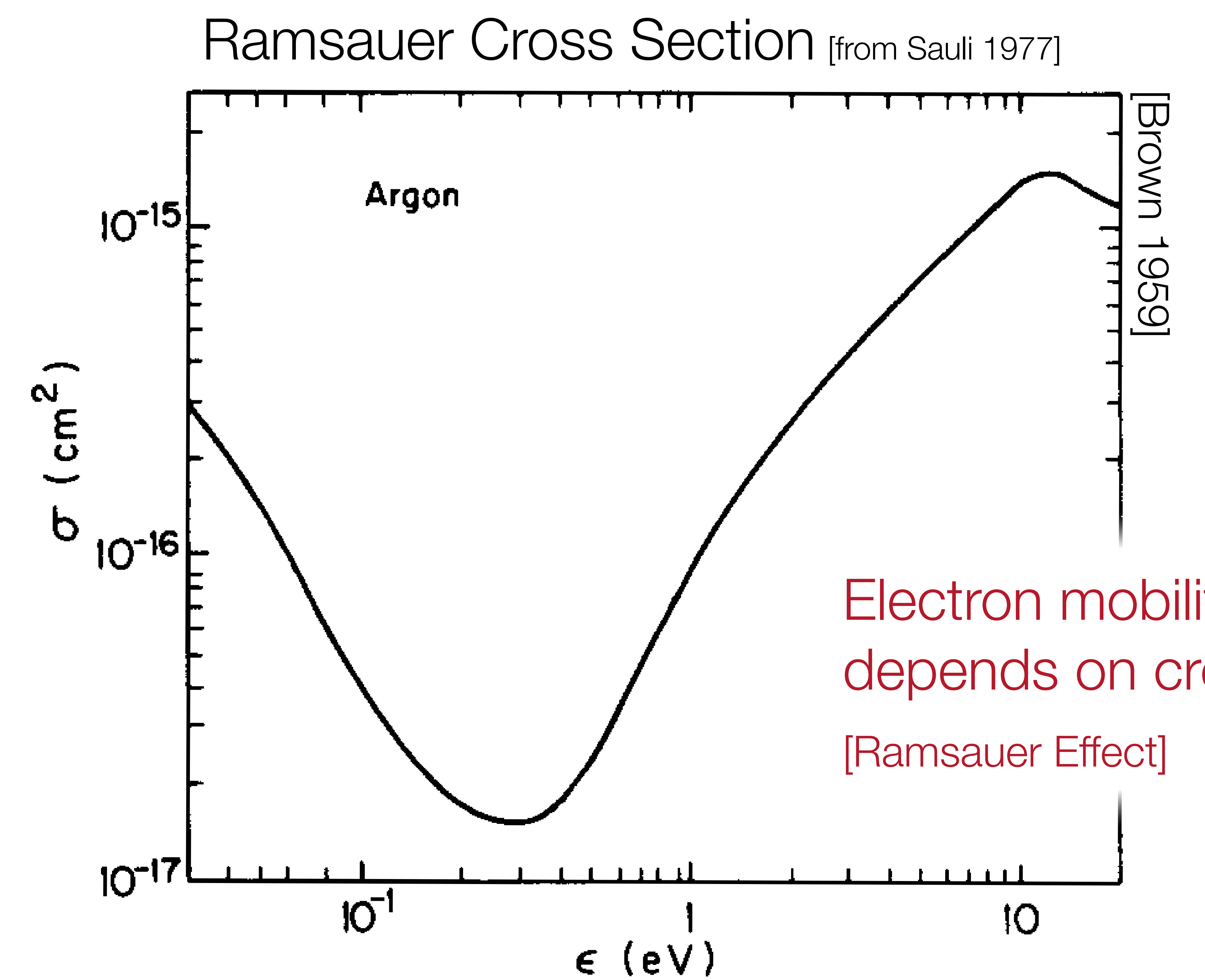
Deslocamento e difusão no gás



Electron mobility depends on cross section

[Ramsauer Effect]

Perda de elétrons

Electrons maybe lost during drift ...
Possible processes:

i. recombination of ions and electrons

Depends on number of charge carriers and recombination coefficient ...

Generally not important ...

Recombination rate:

$$\Lambda = p_r \cdot n^+ n^-$$

➥ Recombination coefficient ≈ 10^{-7} cm^3/s

ii. electron attachment

Electro-negative gases bind electrons; e.g.: O_2, Freon, Cl_2, SF_6 ...
Attachment coefficient h strongly energy dependent ("Ramsauer effect") ...

Example O_2: $h = 10^{-4}$

Collisions of electron per second: 10^{11}
Typical drift time of electron: 10^{-6} s

Fraction lost: $X_{loss} = 10^{-4}\ 10^{11}\ s^{-1}\ 10^{-6}\ s \cdot p = 10p$
$X_{loss} < 1\% \rightarrow p < 10^{-3}$, i.e. less than 1 ‰ admixture

Oxygen should be kept out

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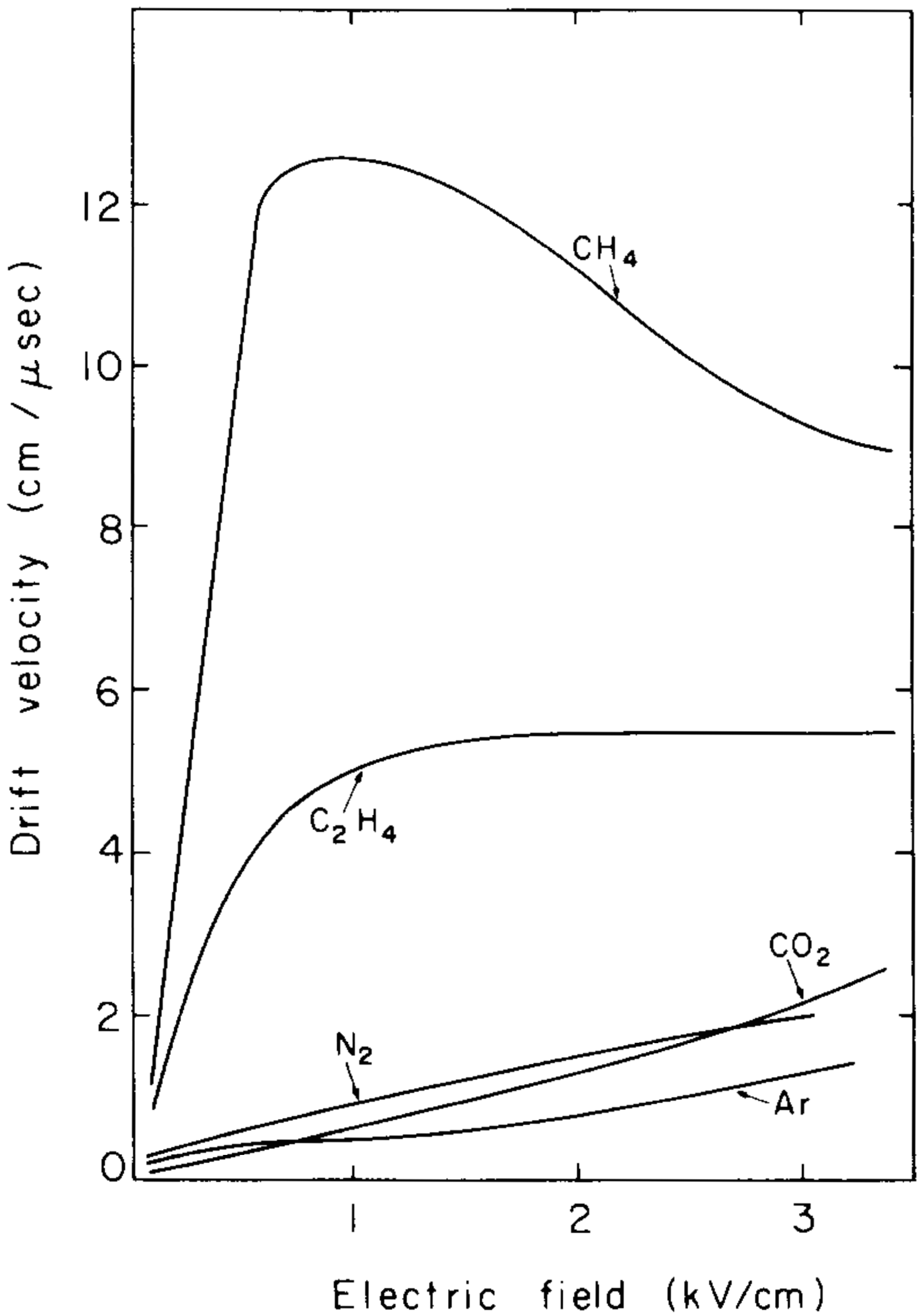
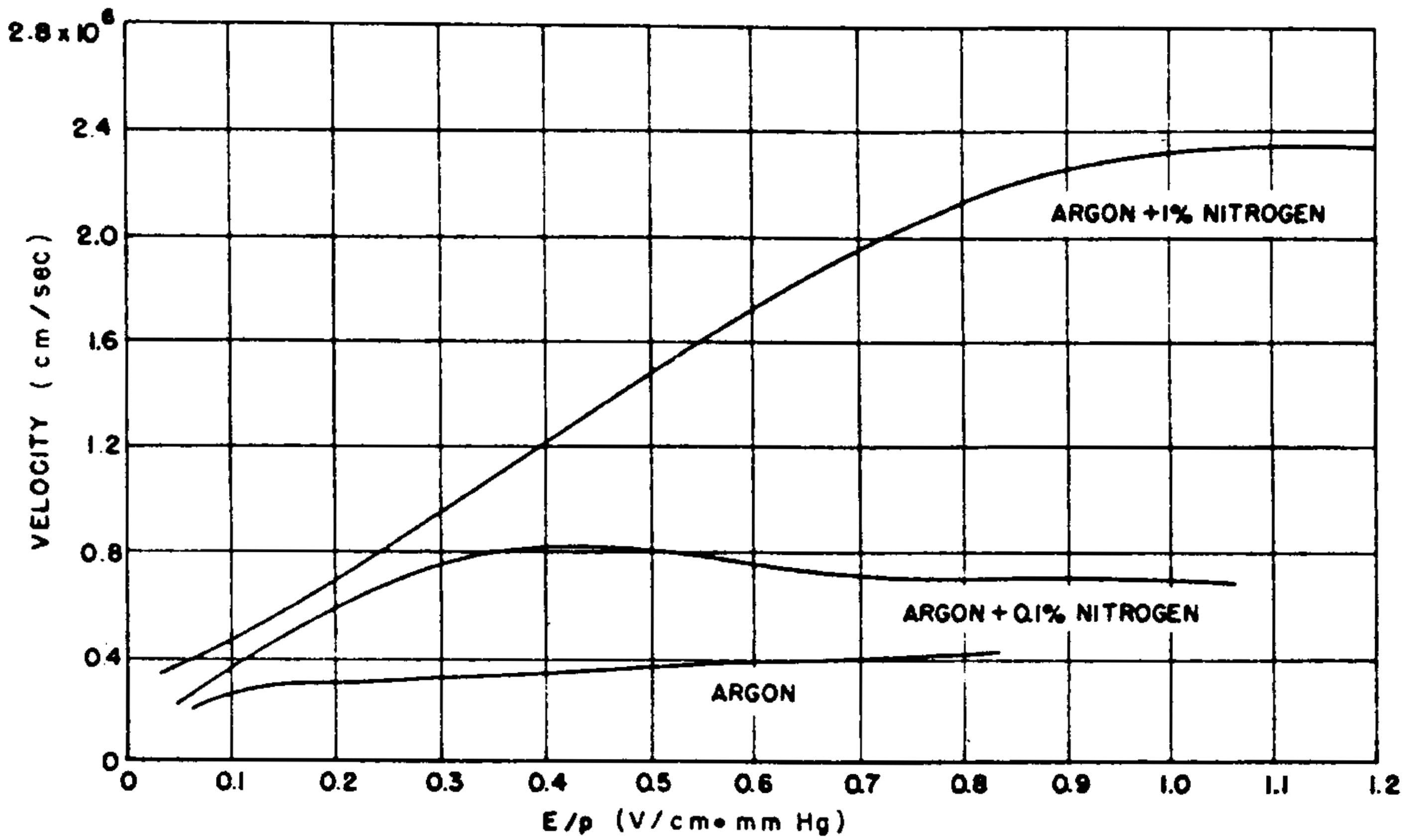
Deslocamento e difusão no gás



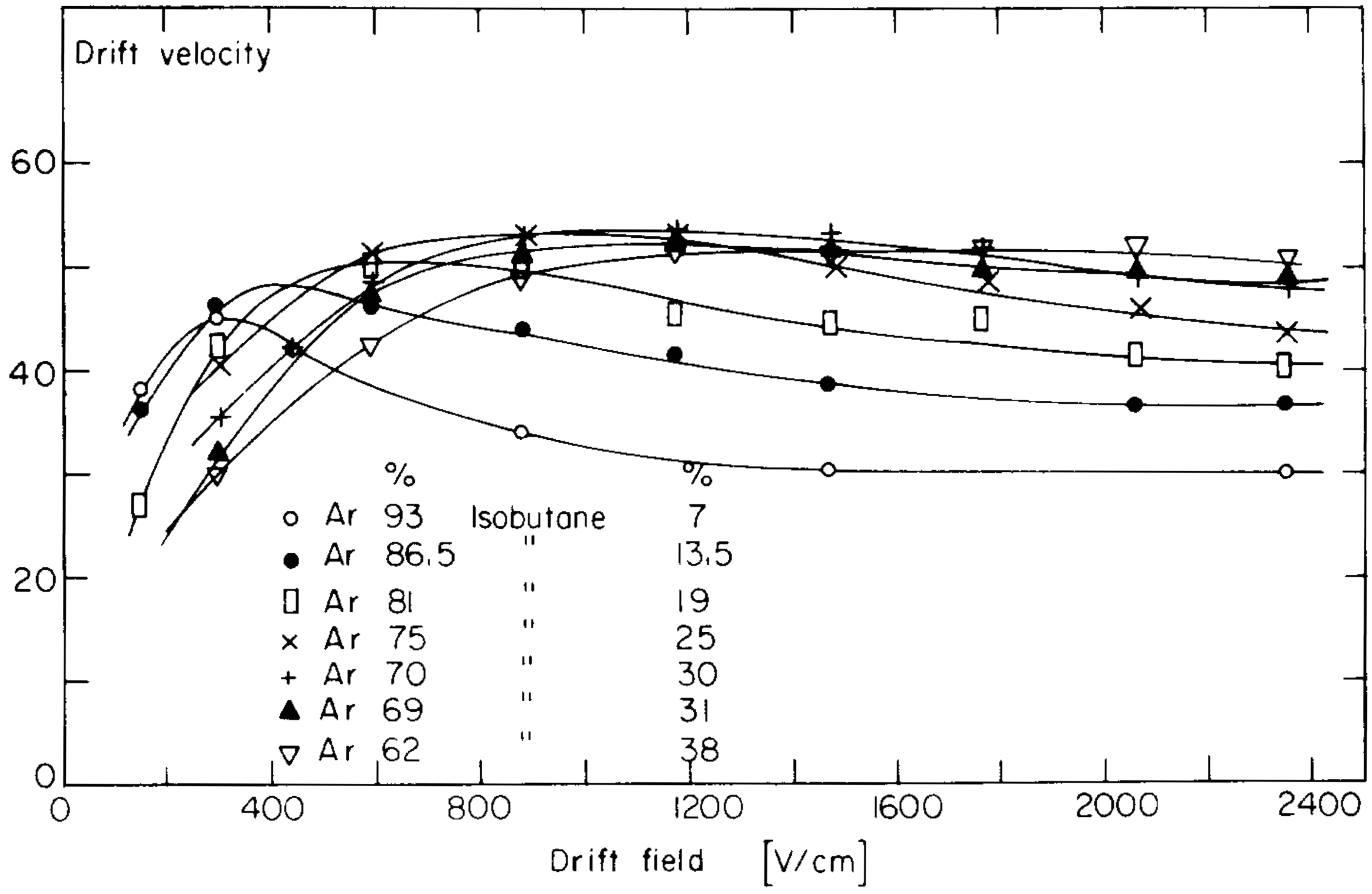
Drift velocity of electrons
in several gases at normal conditions

Use gas mixture to obtain constant v_D
Important for applications using drift time to get
spatial information



E-Field/pressure

Deslocamento e difusão no gás



Drift velocity in several argon-isobutane (C_4H_{10}) mixtures

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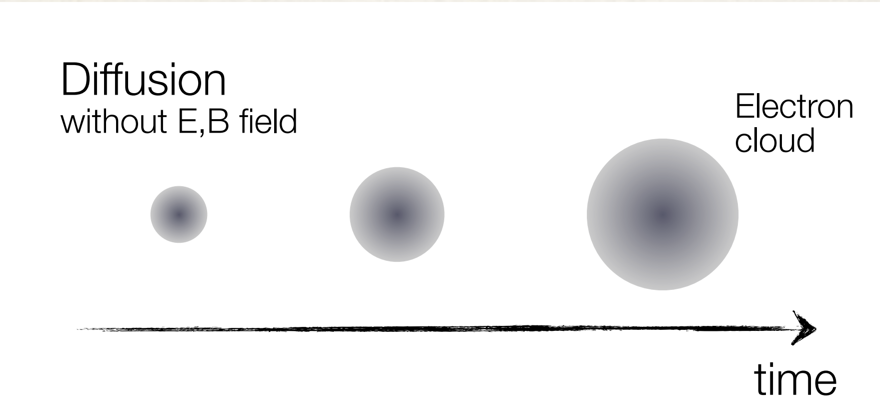
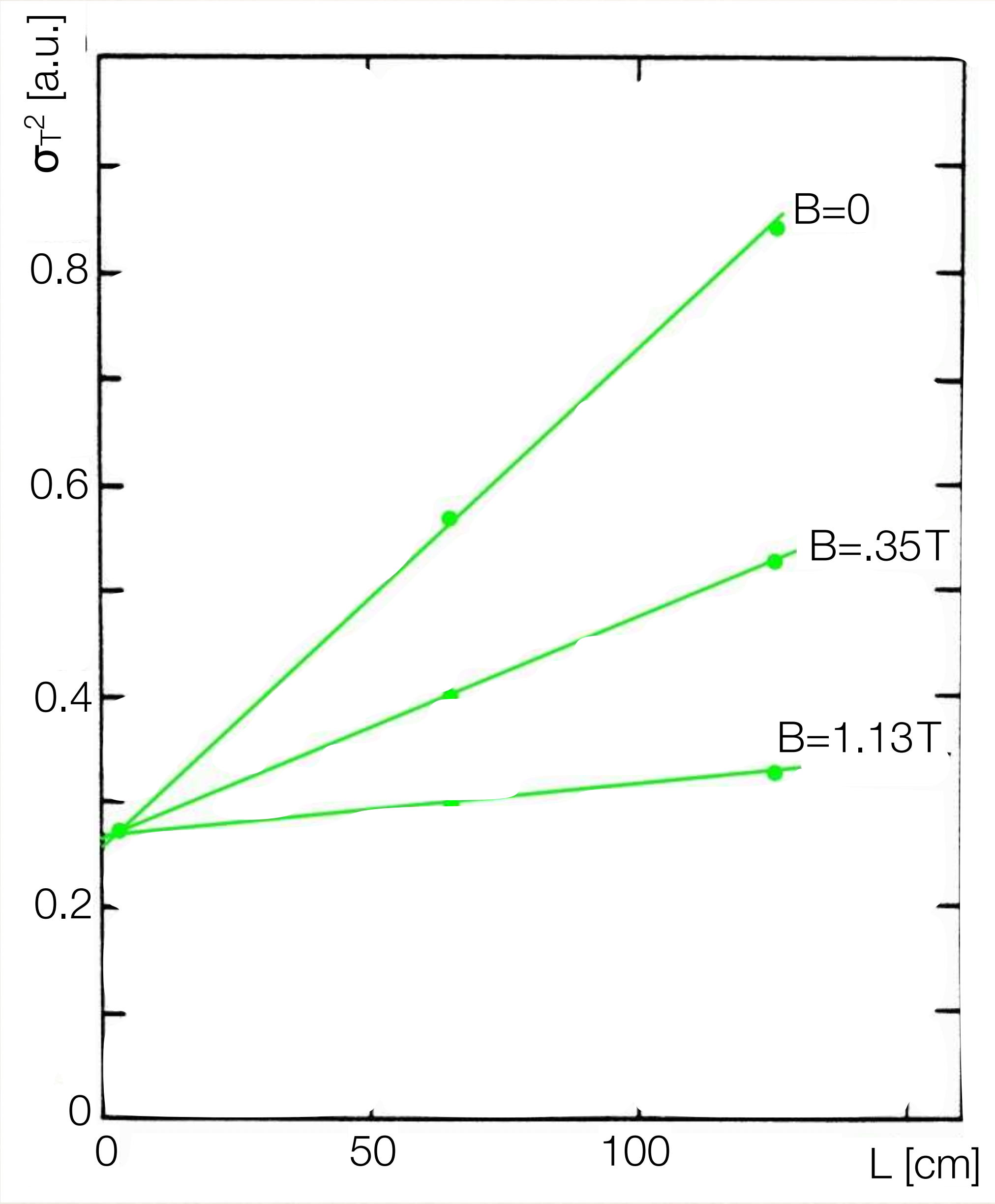
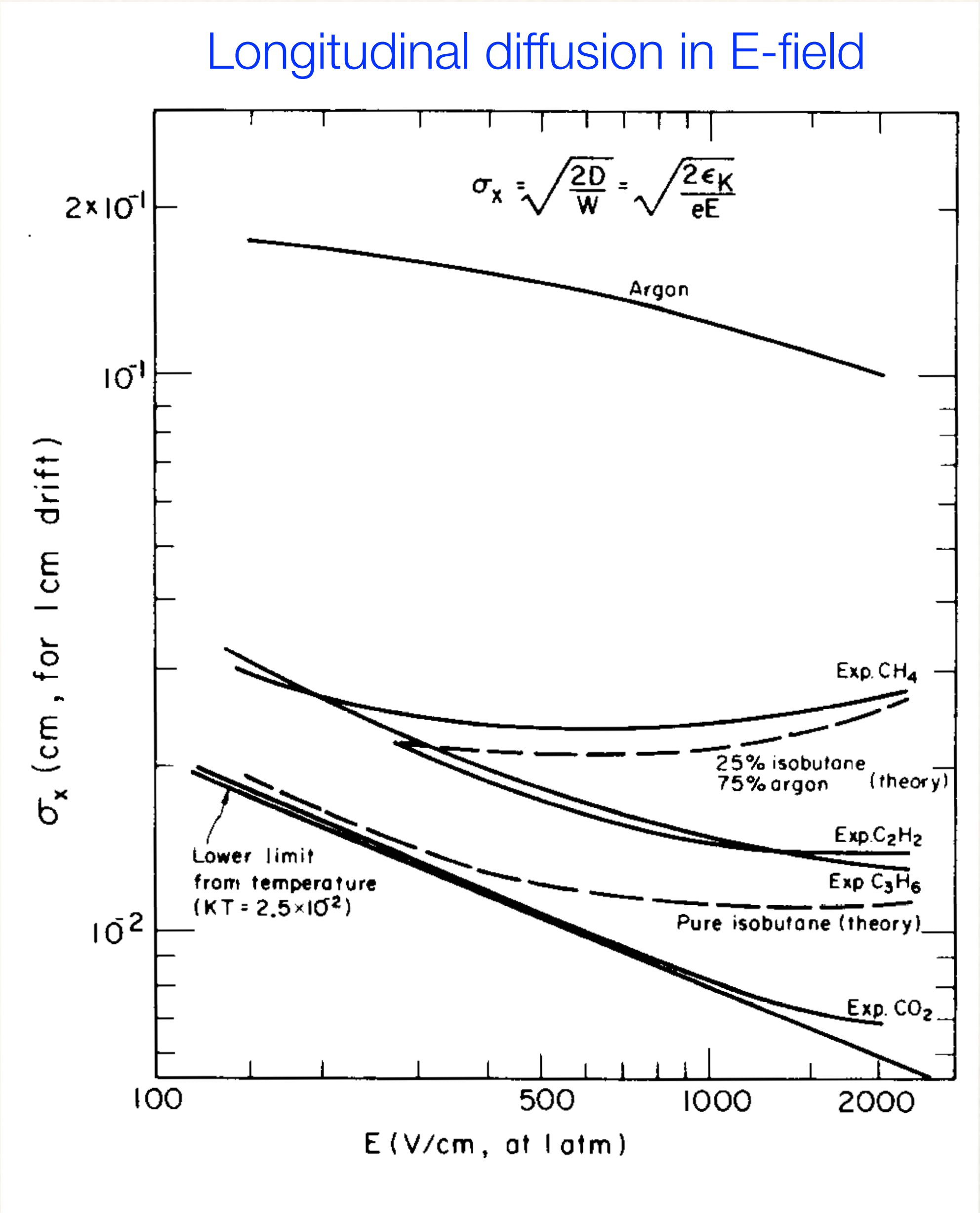
Deslocamento e difusão no gás







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Multiplicação em avalanche

Large electric field yields
large kinetic energy of electrons ...

➛ Avalanche formation

Larger mobility of electrons results in liquid
drop like avalanche with electrons near head ...

Mean free path: λ_{ion}
[for a secondary ionization]

Probability of an ionization per
unit path length: $\alpha = 1/\lambda_{ion}$ [1st Townsend coefficient]

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

$$n = n_0 e^{\alpha x}$$

n(x) = electrons
at location x

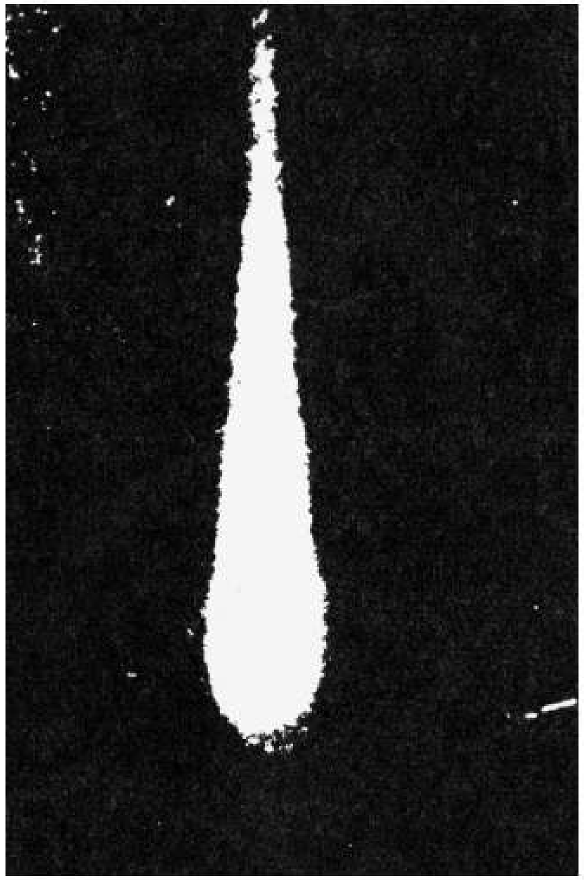
Gain:

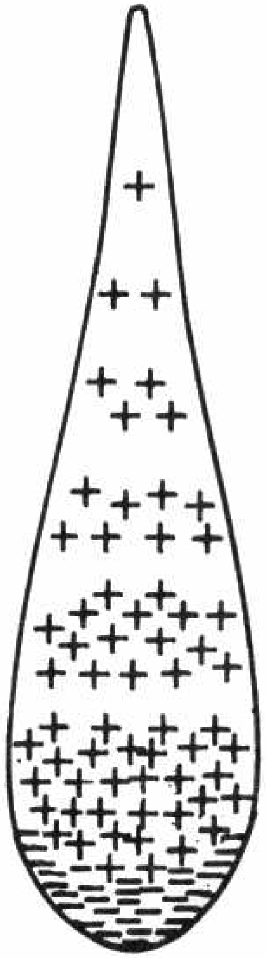
$$G = \frac{n}{n_0} = e^{\alpha x}$$

and more general for $\alpha = \alpha(x)$: $$G = \frac{n}{n_0} = \exp\left[\int_{x_1}^{x_2} \alpha(x) dx\right]$$

[Raether limit: $G \approx 10^8$; $\alpha x = 20$; then sparking sets in ...]

Townsend avalanche





Drop-like shape of an avalanche
Left: cloud champer picture
Right: schematic view

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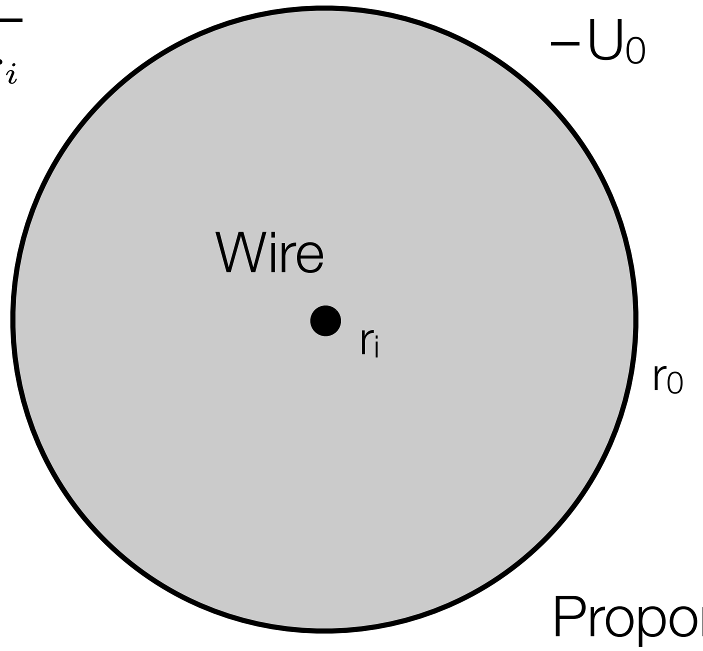
Multiplicação em avalanche

To reach high E fields
use a thin wire as anode ...

Close to wire E-field very large ...

$$E = \frac{U_0}{r \, \ln {}^{r_0}/_{r_i}}$$



Proportional Counter

Kinetic energy:

$$\Delta T_{\text{kin}} = e\Delta U = e\int_{r_1}^{r_2} E(r)dr$$

$$= \frac{eU_0}{\ln {}^{r_0}/_{r_i}} \int_{r_1}^{r_2} \frac{1}{r}\, dr$$

$$= \underbrace{\frac{eU_0}{\ln {}^{r_0}/_{r_i}}}_{\text{const.}} \cdot \ln {}^{r_2}/_{r_1}$$

Choose ratio as
large as possible with small Δr ...

[Δr should be smaller than typical mean free path ...]

Reminder Physics II:

$$\text{div}\vec{E} = \frac{\rho}{\epsilon_0} \qquad \oint \vec{E}\, dA = \int \frac{\rho}{\epsilon_0}\, d^3r$$

$$\rightarrow \; |\vec{E}| = \frac{\lambda}{2\pi\epsilon_0}\,\frac{1}{r} \qquad 2\pi r\, L \cdot |\vec{E}| = {}^{Q}/_{\epsilon_0}$$

$$\lambda = {}^{Q}/_{L}$$

linear charge density

$$U_0 = \int_{r_i}^{r_0} E\, dr = \frac{\lambda}{2\pi\epsilon_0} \ln \frac{r_0}{r_i}$$

$$\rightarrow \; \frac{\lambda}{2\pi\epsilon_0} = \frac{U_0}{\ln {}^{r_0}/_{r_i}}$$

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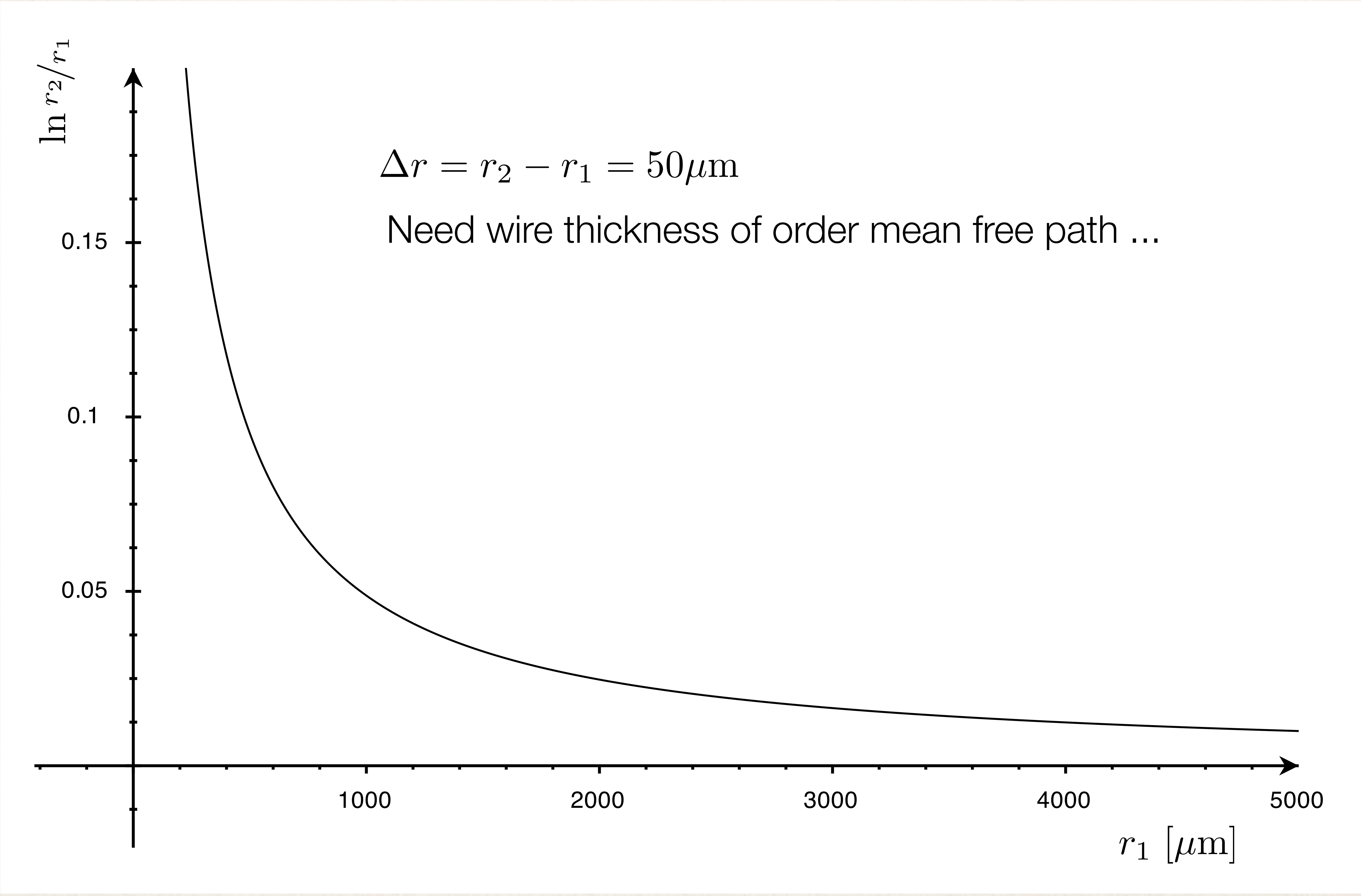
Multiplicação em avalanche



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Single wire proportional counter

Ionization mode:

full charge collection
no multiplication; gain ≈ 1

Proportional mode:

multiplication of ionization
signal proportional to ionization
measurement of dE/dx
secondary avalanches need quenching;
gain ≈ $10^4 - 10^5$

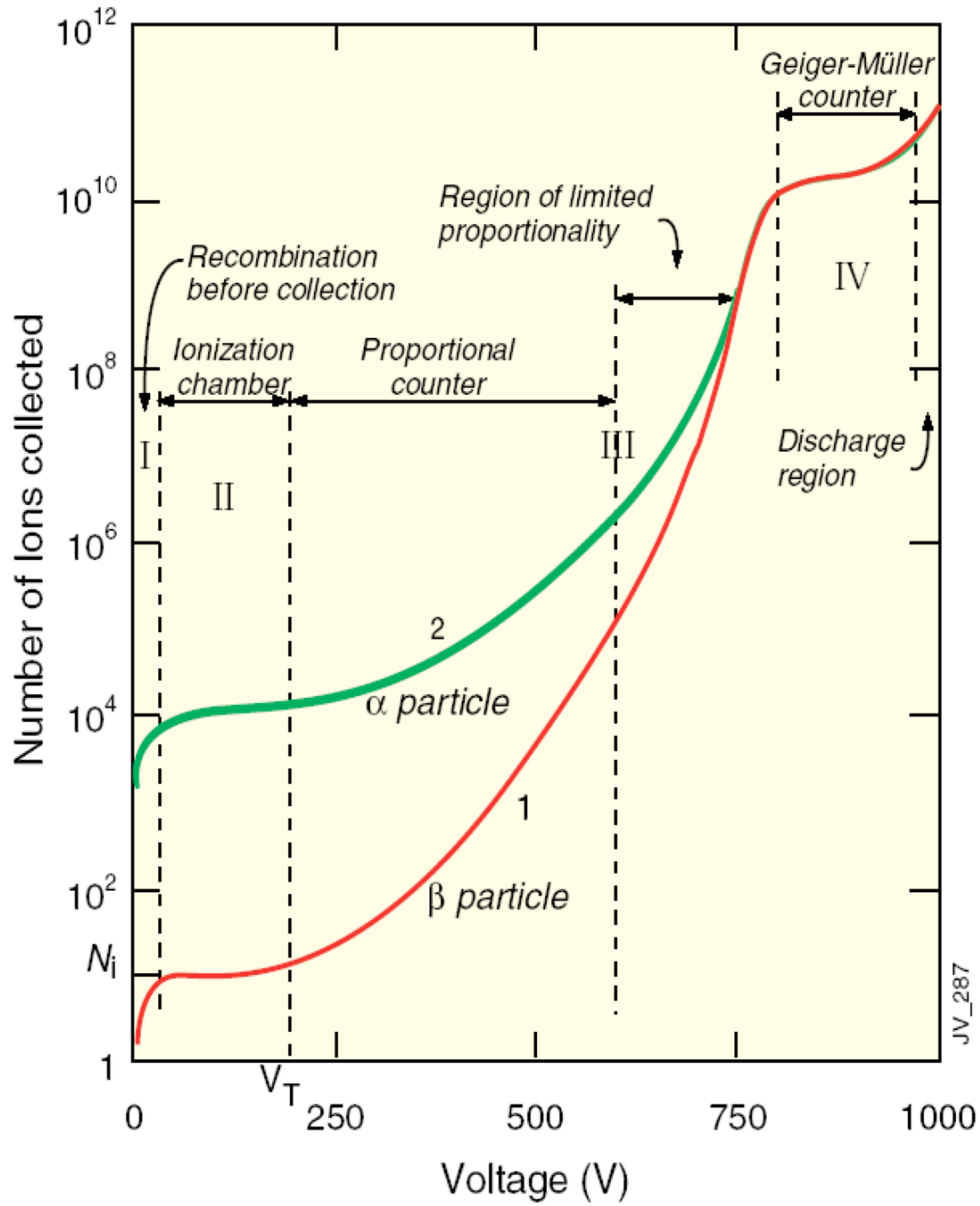
Limited proportional mode:

[saturated, streamer]

strong photoemission
requires strong quenchers or pulsed HV;
gain ≈ 10^{10}

Geiger mode:

massive photoemission;
full length of the anode wire affected;
discharge stopped by HV cut



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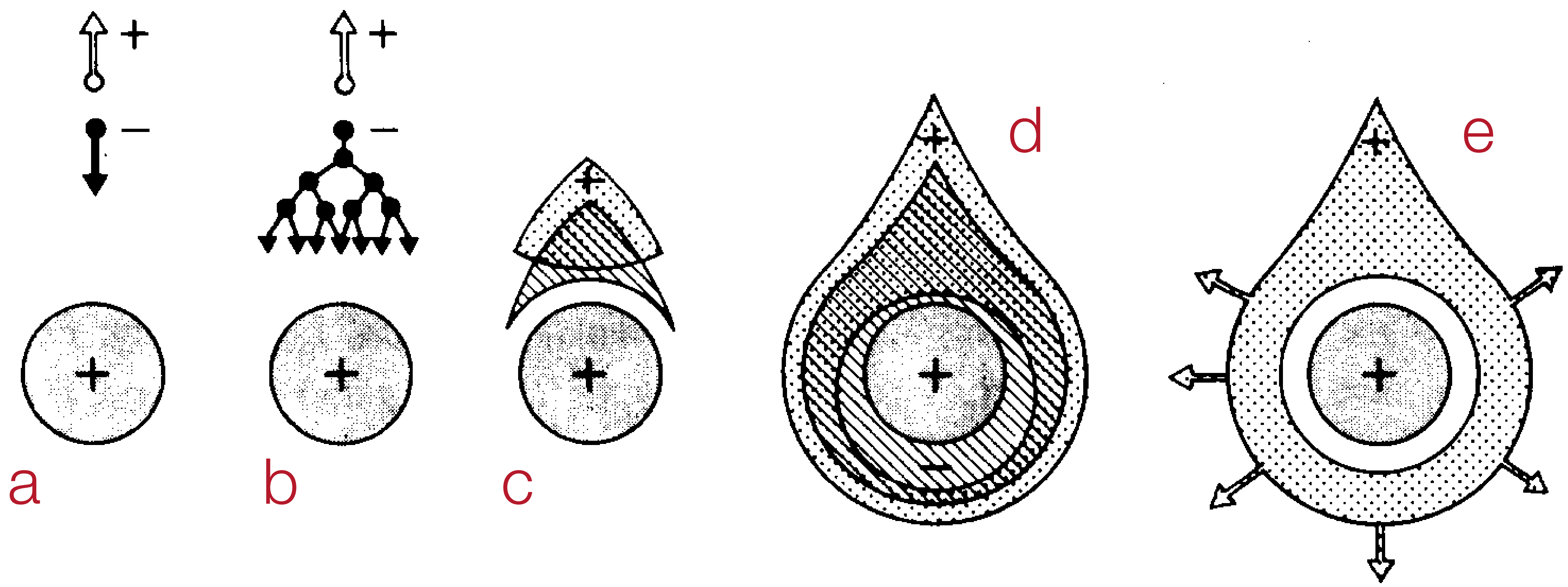
Deslocamento e difusão no gás



Time development of an avalanche in a proportional counter

A single primary electron proceeds towards anode in regions of increasingly high fields, experiencing ionizing collisions; due to the lateral diffusion, a drop-like avalanche, surrounding the wire develops.

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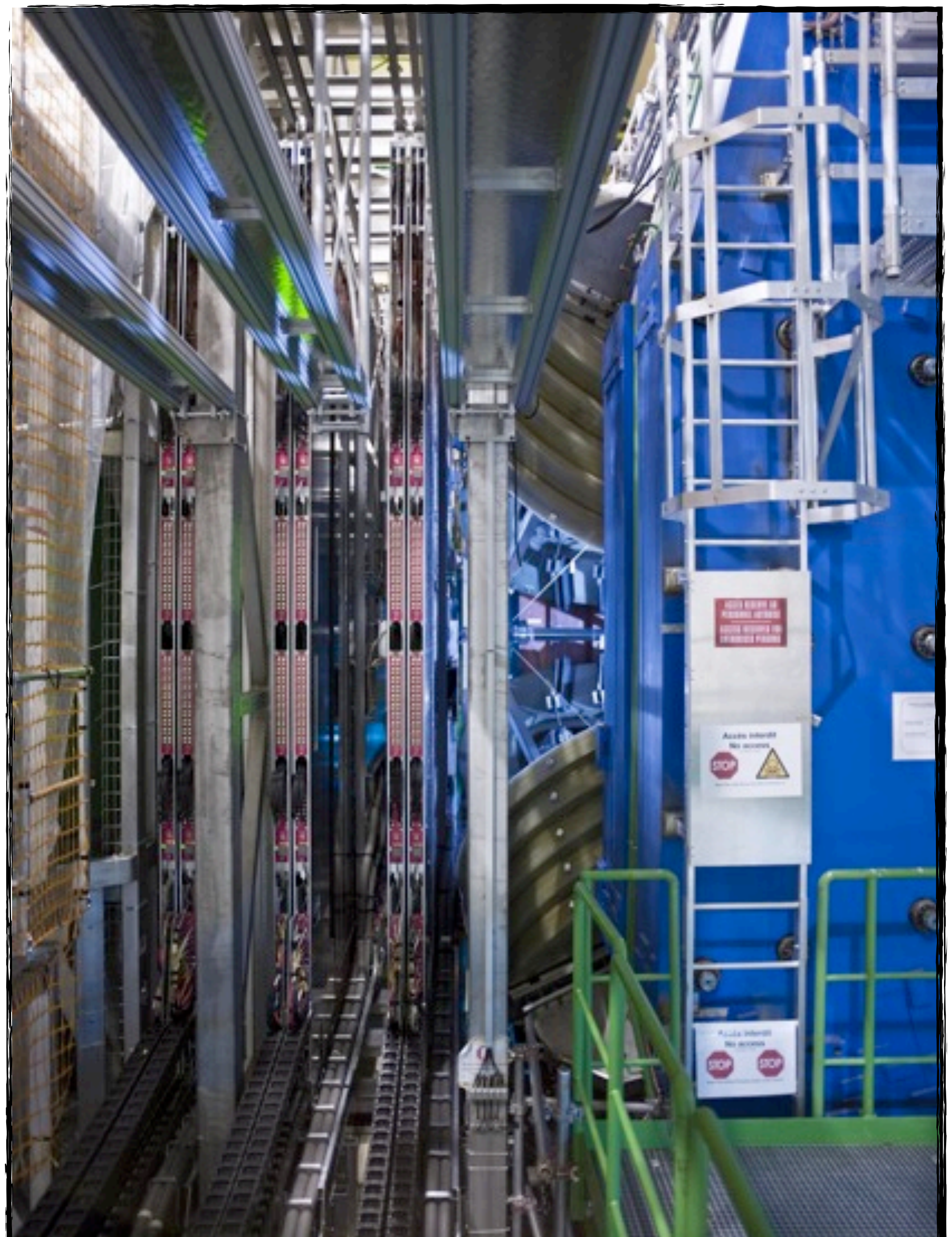
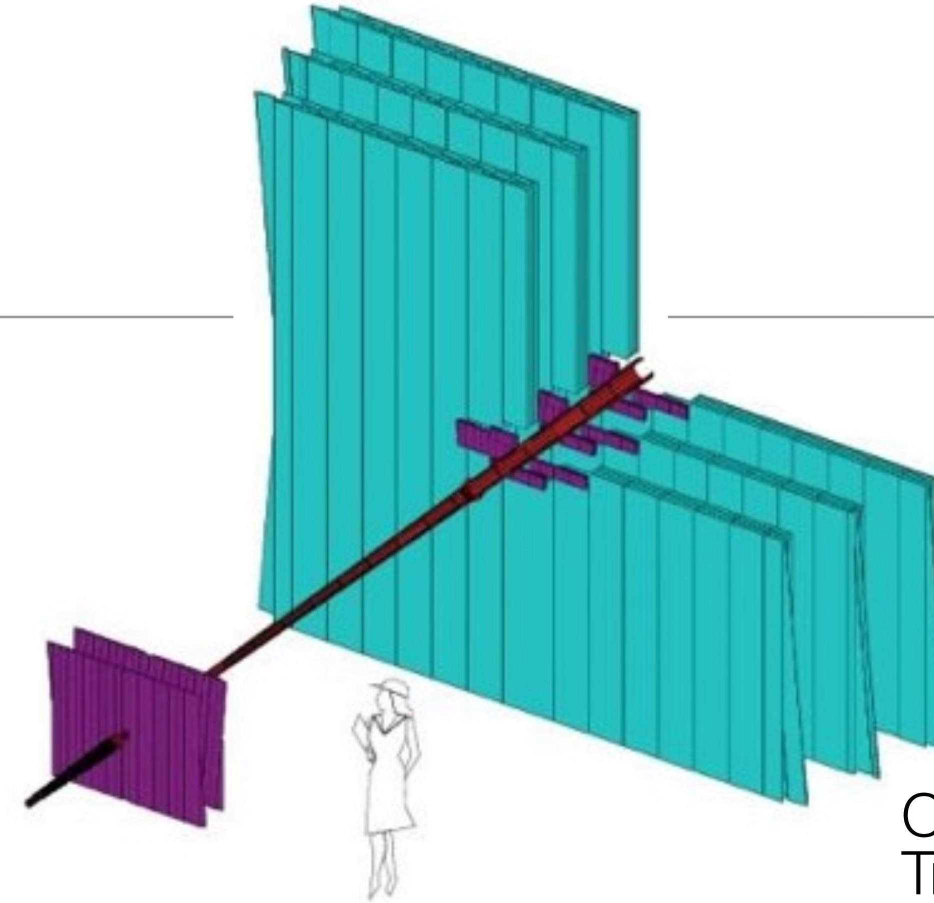
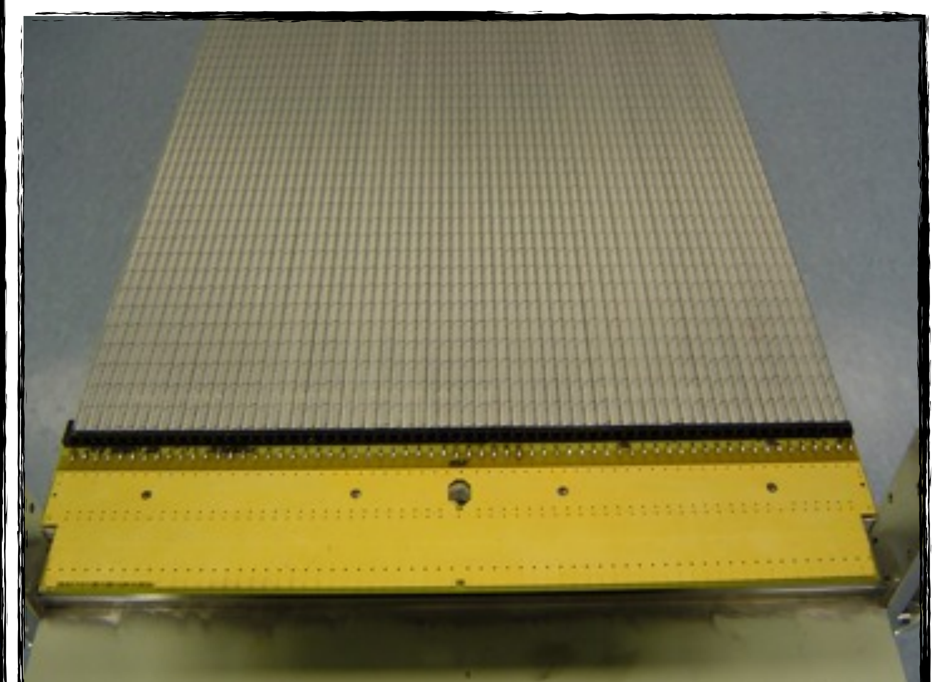
LHCb Outer Tracker

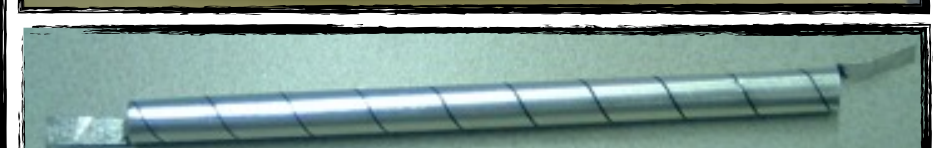




Outer
Tracker



Straw Tubes
[double layers]



3 Chambers
[4 layers á 18 modules]

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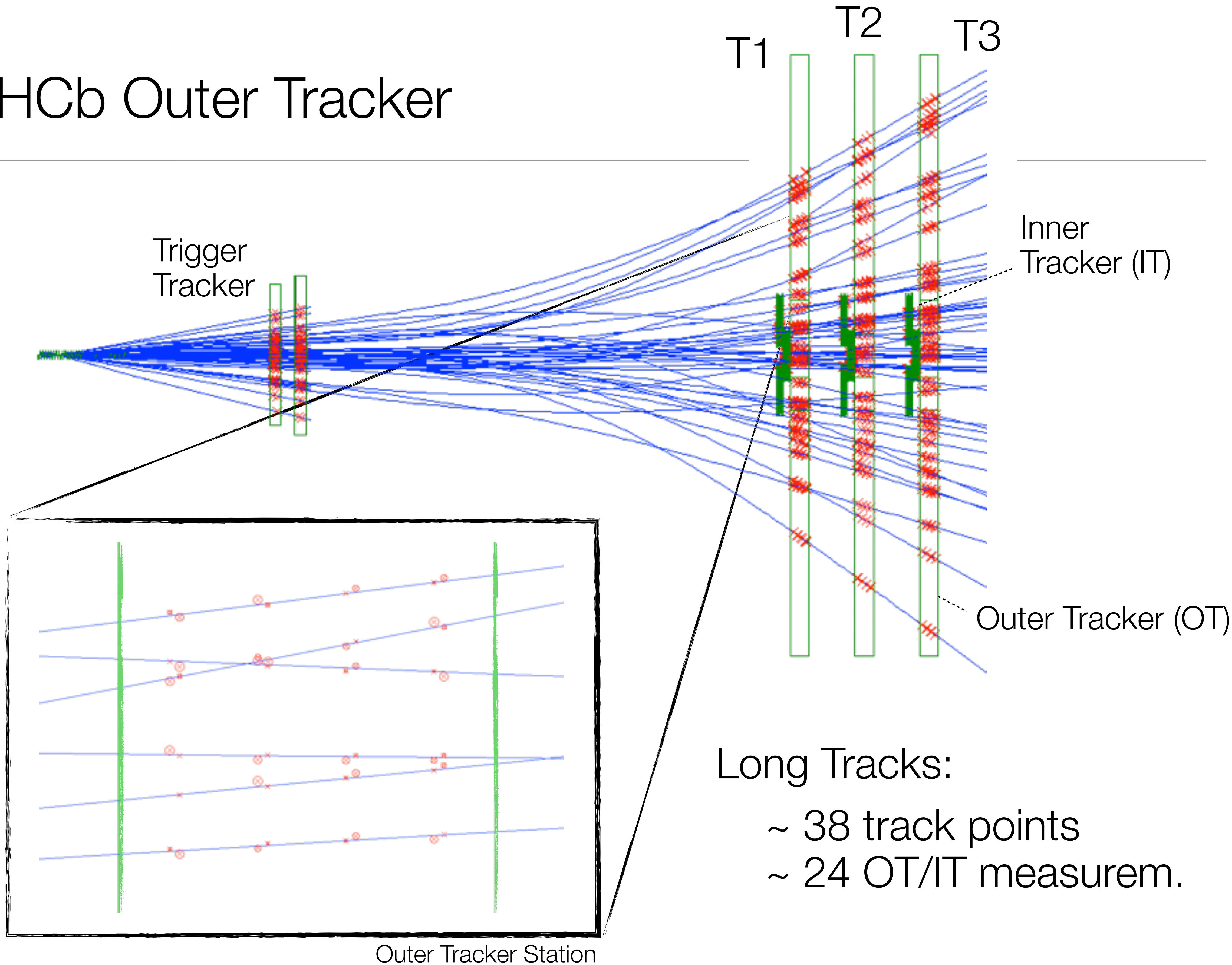
LHCb Outer Tracker



Long Tracks:

~ 38 track points
~ 24 OT/IT measurem.

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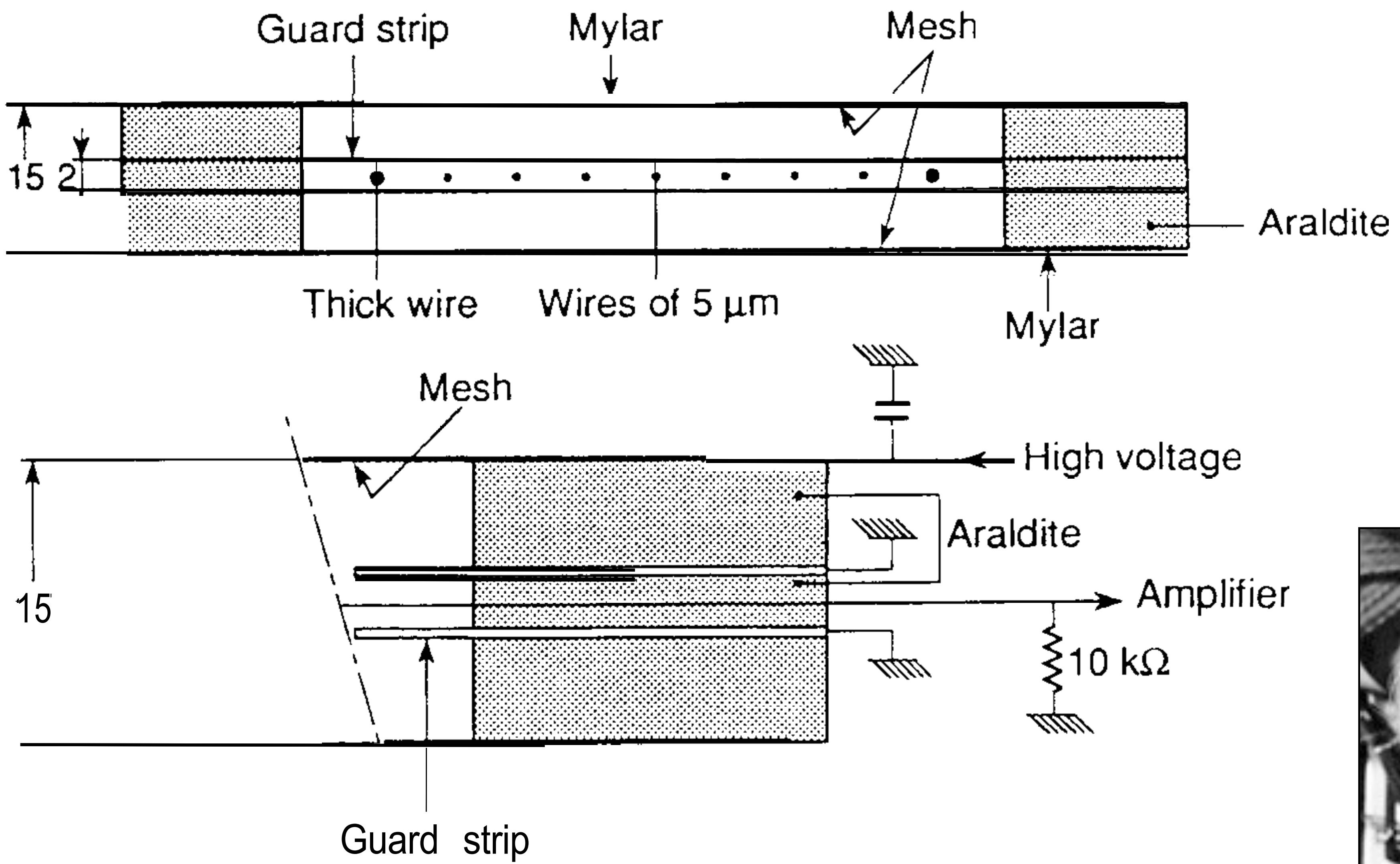
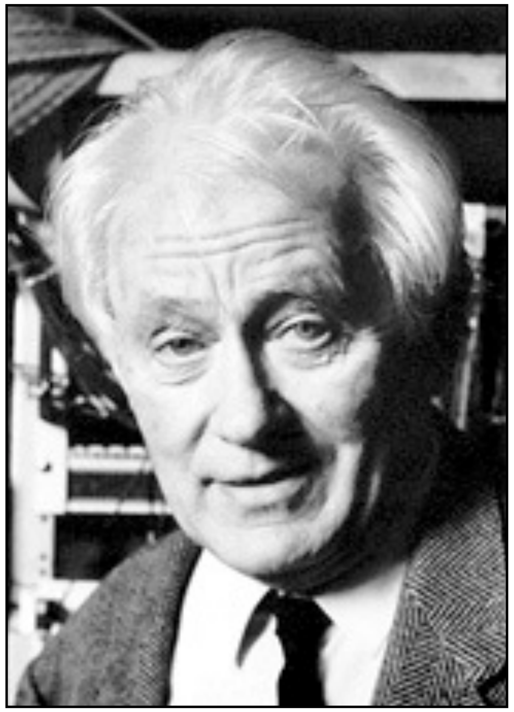
Multi-wire proportional chamber (MWPC)



MWPC construction details
from Charpak's nobel lecture [1967 design]

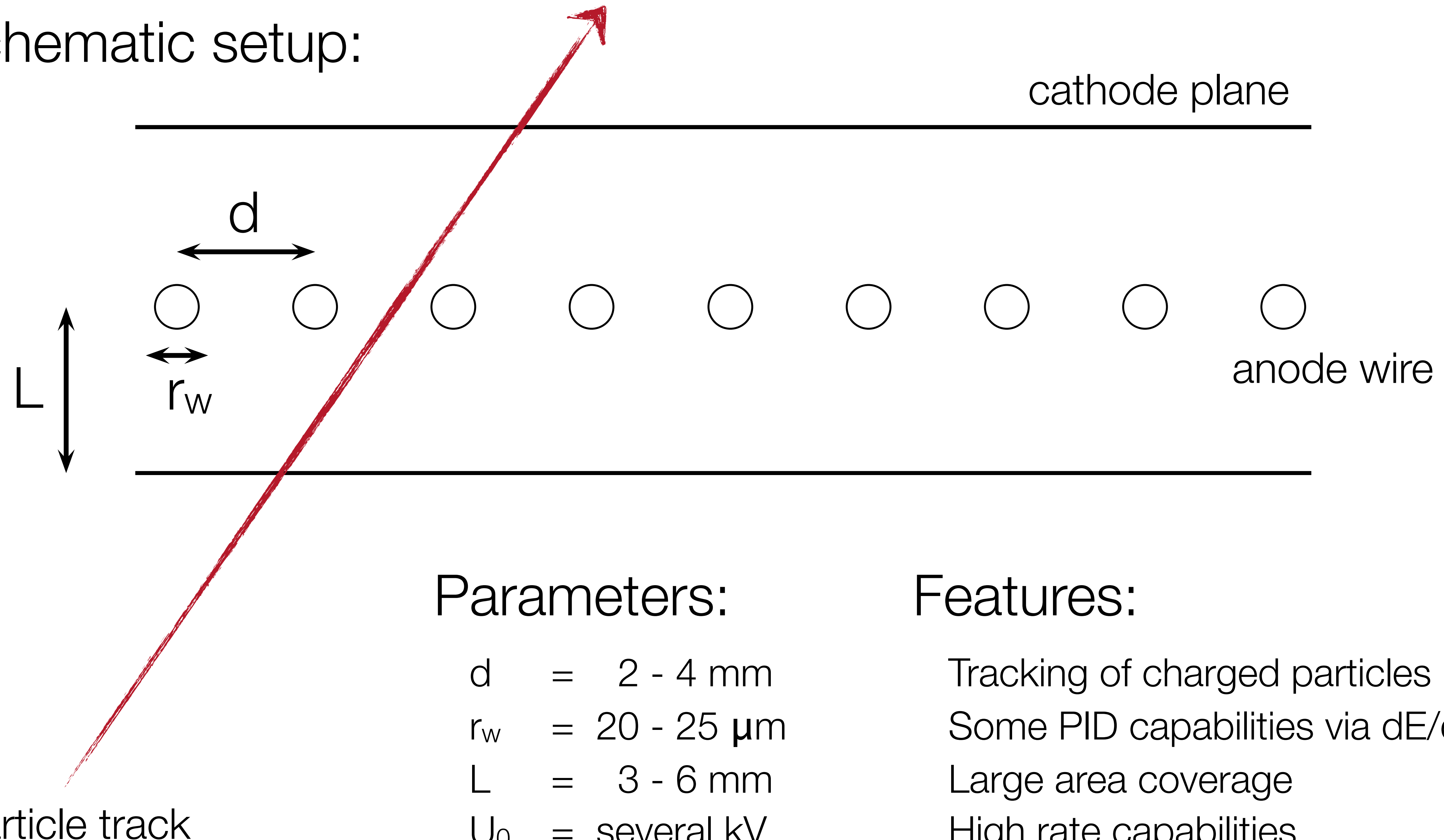
Sense wires [∅ = 20 μm] separated by 2 mm; wires lie between two cathode meshes; edges of the planes are potted in Araldite ...

G. Charpak
Nobel Prize 1992



Multi-wire proportional chamber (MWPC)

Schematic setup:



Parameters:

d	=	2 - 4 mm
r_w	=	20 - 25 µm
L	=	3 - 6 mm
U_0	=	several kV

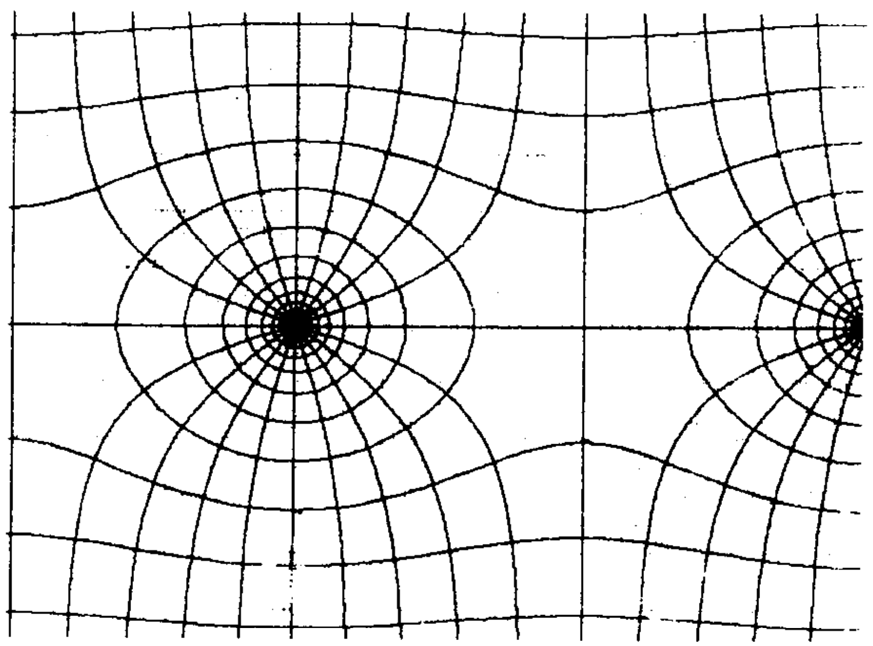
Total area: $O(m^2)$

Features:

- Tracking of charged particles
- Some PID capabilities via dE/dx
- Large area coverage
- High rate capabilities

Multi-wire proportional chamber (MWPC)

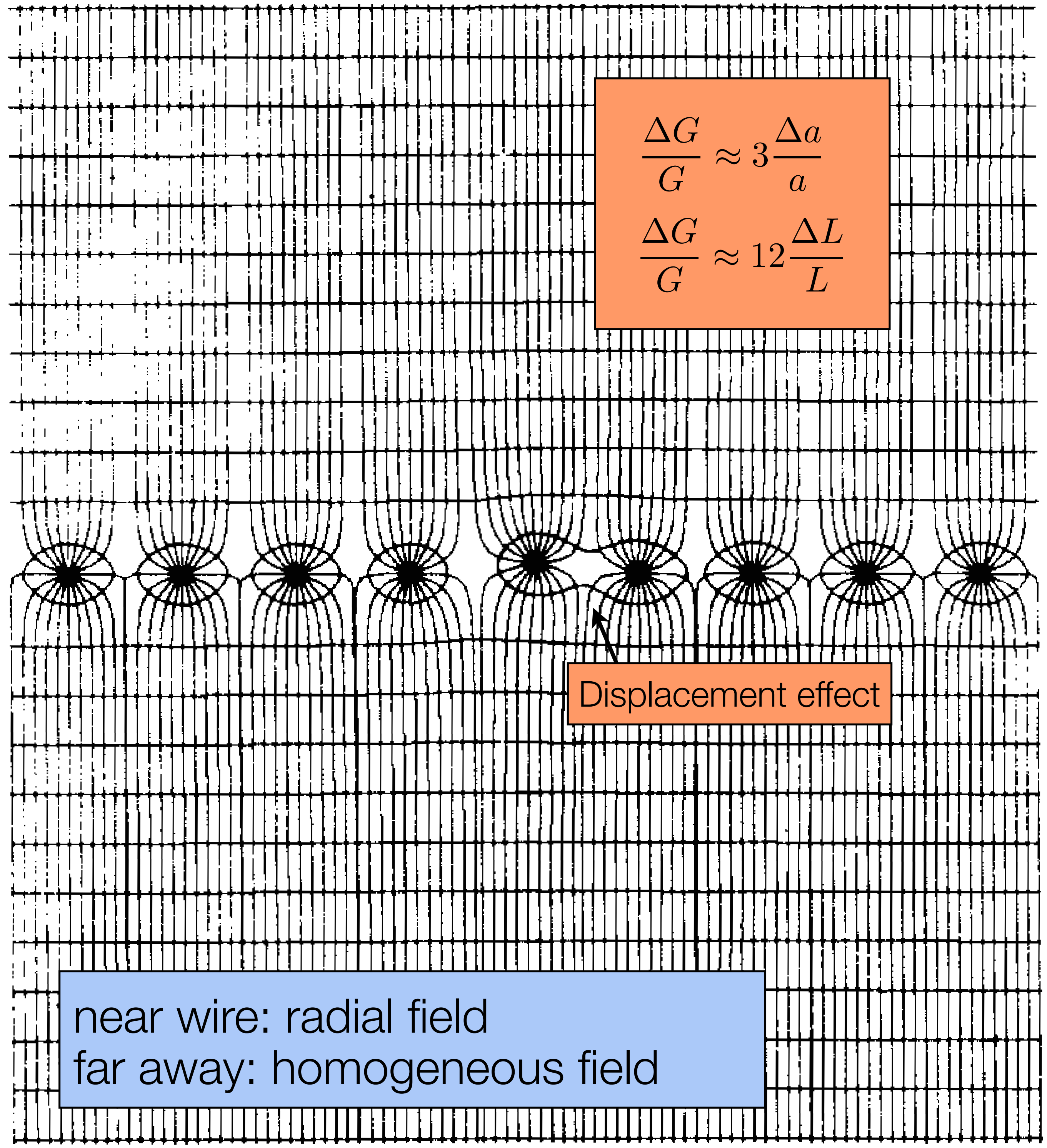
Electric field lines
and equipotentials



Small wire displacements
reduce field quality ...

Need high mechanical precision
both for geometry and wire tension ...

[electrostatics and gravitation; wire sag]



Multi-wire proportional chamber (MWPC)

Signal generation:

Electrons drift to closest wire
Gas amplification near wire ➛ avalanche
Signal generation due to electrons and slow ions ...

main contribution

Timing resolution:

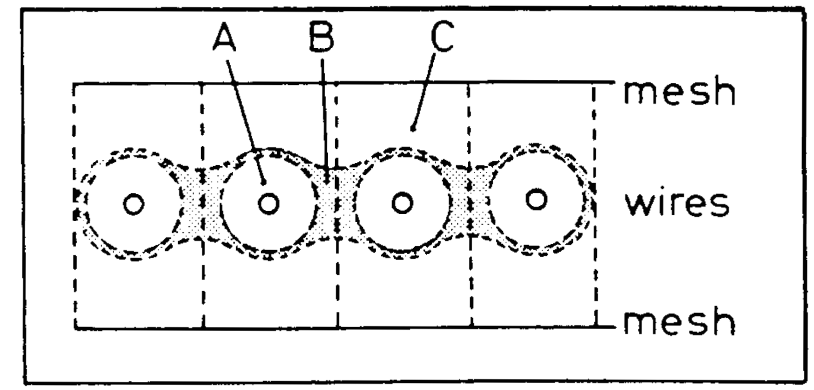
Depends on location of penetration
For fast response: OR of all channels ...
[Typical: σ_t = 10 ns]

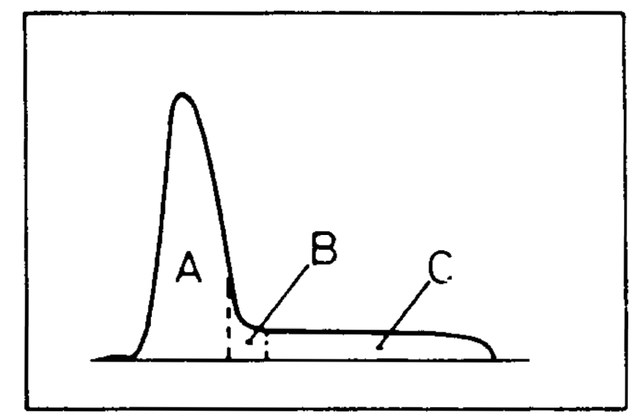
Space point resolution:

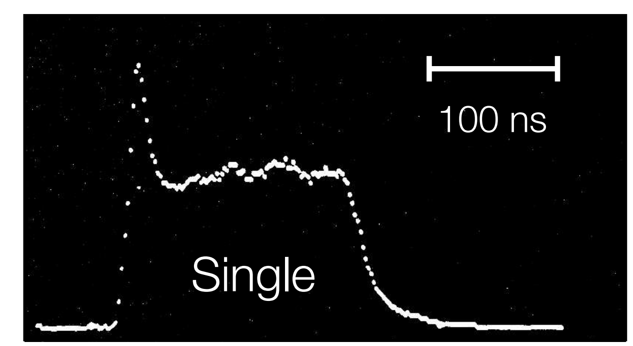
Only information about closest wire ➛ $\sigma_x = d/\sqrt{12}$
[Not very precise and only one for one dimension ...]

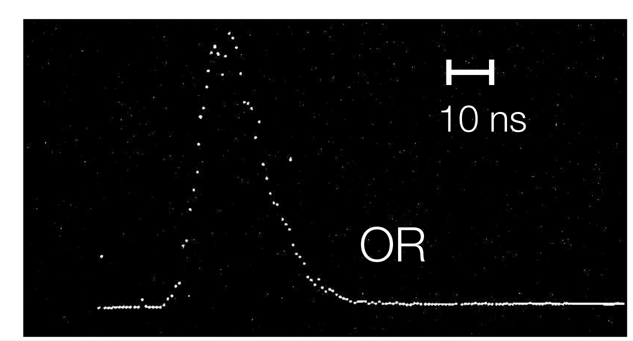
2-dim.: use 2 MWPCs with different orientation ...
3-dim.: several layers of such X-Y-MWPC combinations.

Possible improvement: segmented cathode ...









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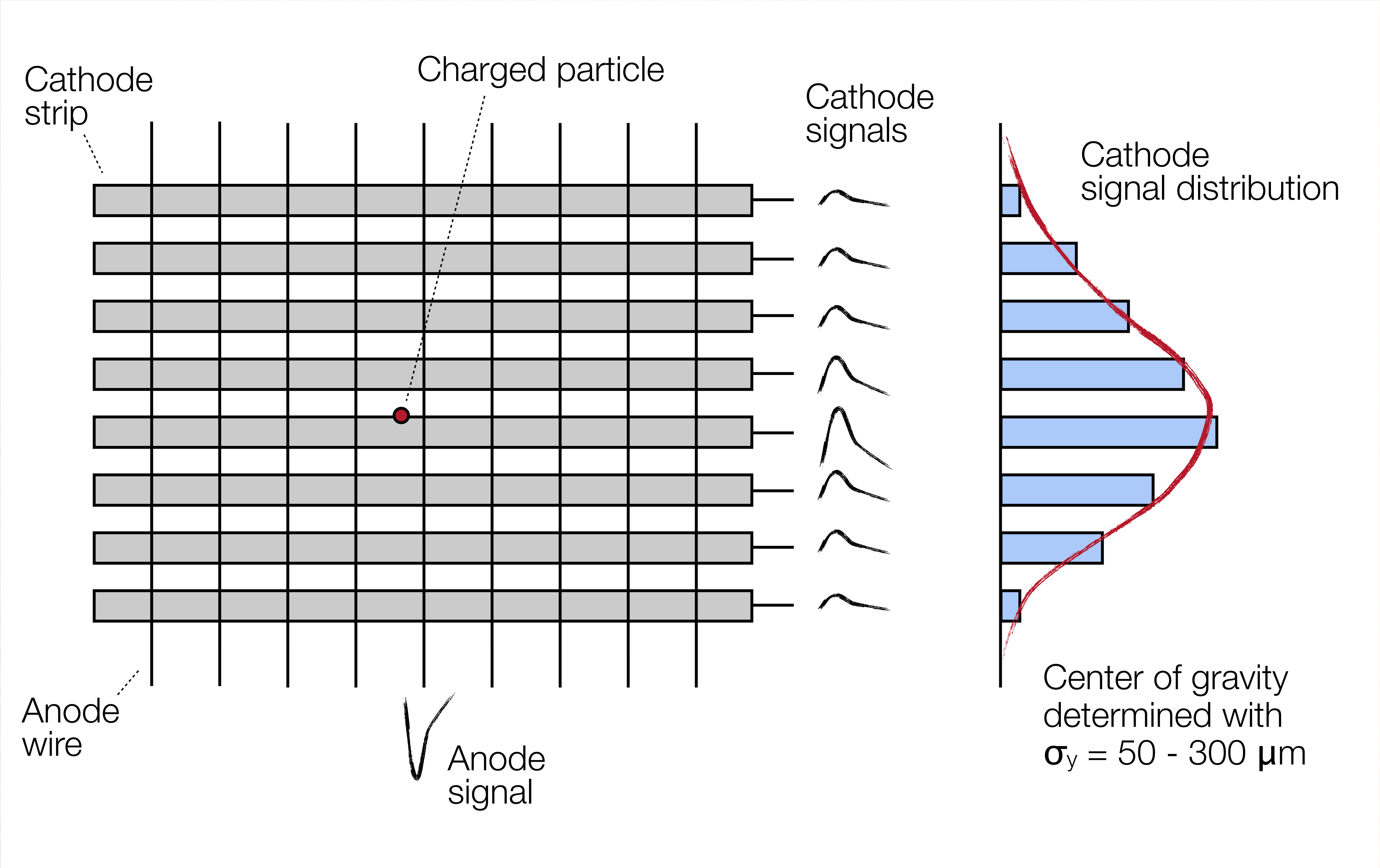
Multi-wire proportional chamber (MWPC)



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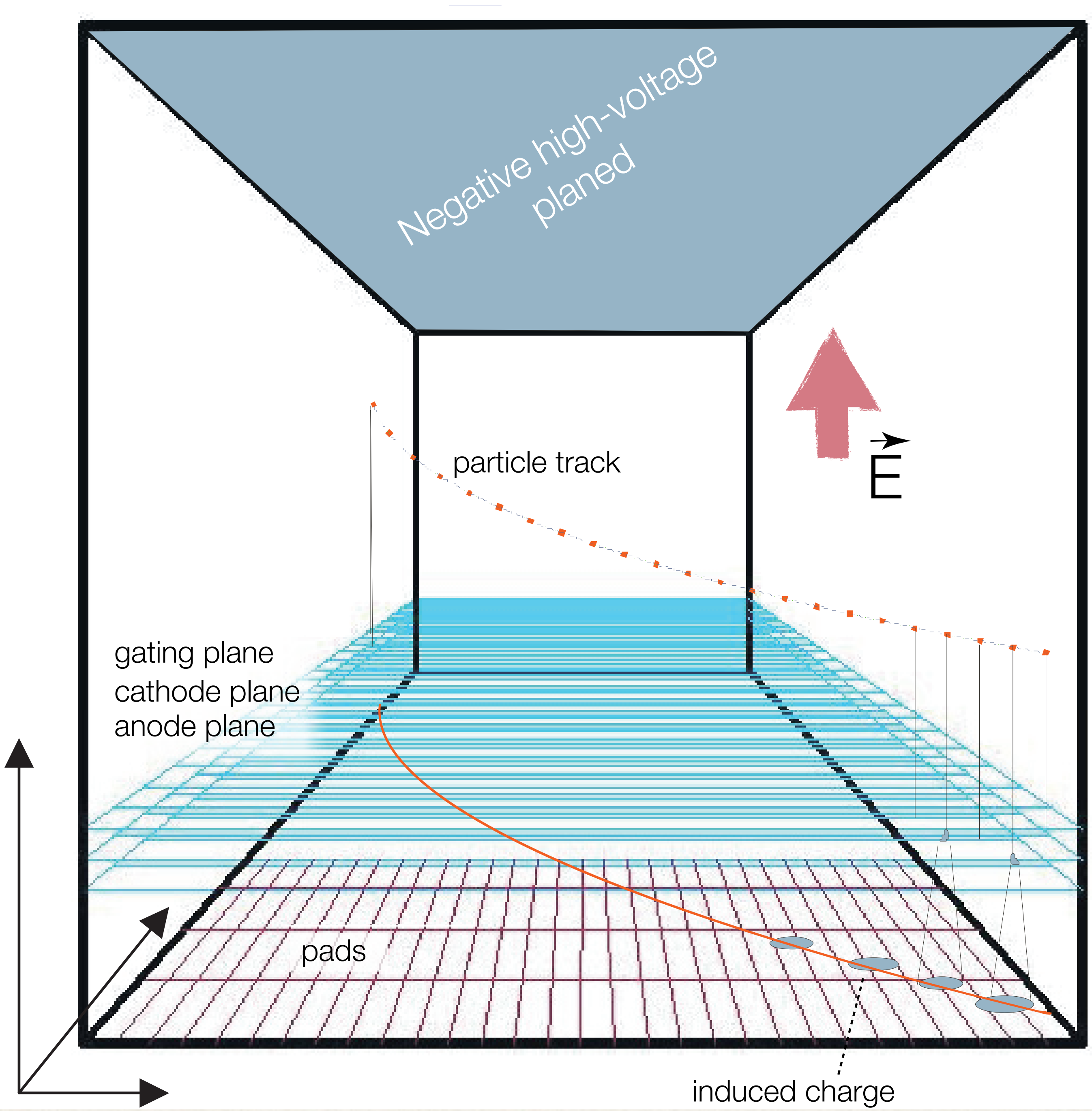
Time projection chamber (TPC)



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Advantages:

- Complete track within one detector yields good momentum resolution
- Relative few, short wires (MWPC only)
- Good particle ID via dE/dx
- Drift parallel to B suppresses transverse diffusion by factors 10 to 100

Challenges:

- Long drift time; limited rate capability [attachment, diffusion ...]
- Large volume [precision]
- Large voltages [discharges]
- Large data volume ...
- Extreme load at high luminosity; gating grid opened for triggered events only ...

Typical resolution:

z: mm; x: 150 - 300 μm; y: mm
dE/dx: 5 - 10%

Time projection chamber (TPC)

ALICE TPC:

Length: 5 meter
Radius: 2.5 meter
Gas volume: 88 m^3

Total drift time: 92 μs
High voltage: 100 kV

End-cap detectors: 32 m^2
Readout pads: 557568

159 samples radially
1000 samples in time

Gas: $Ne/CO_2/N_2$ (90-10-5)
Low diffusion (cold gas)

Gain: > 10^4

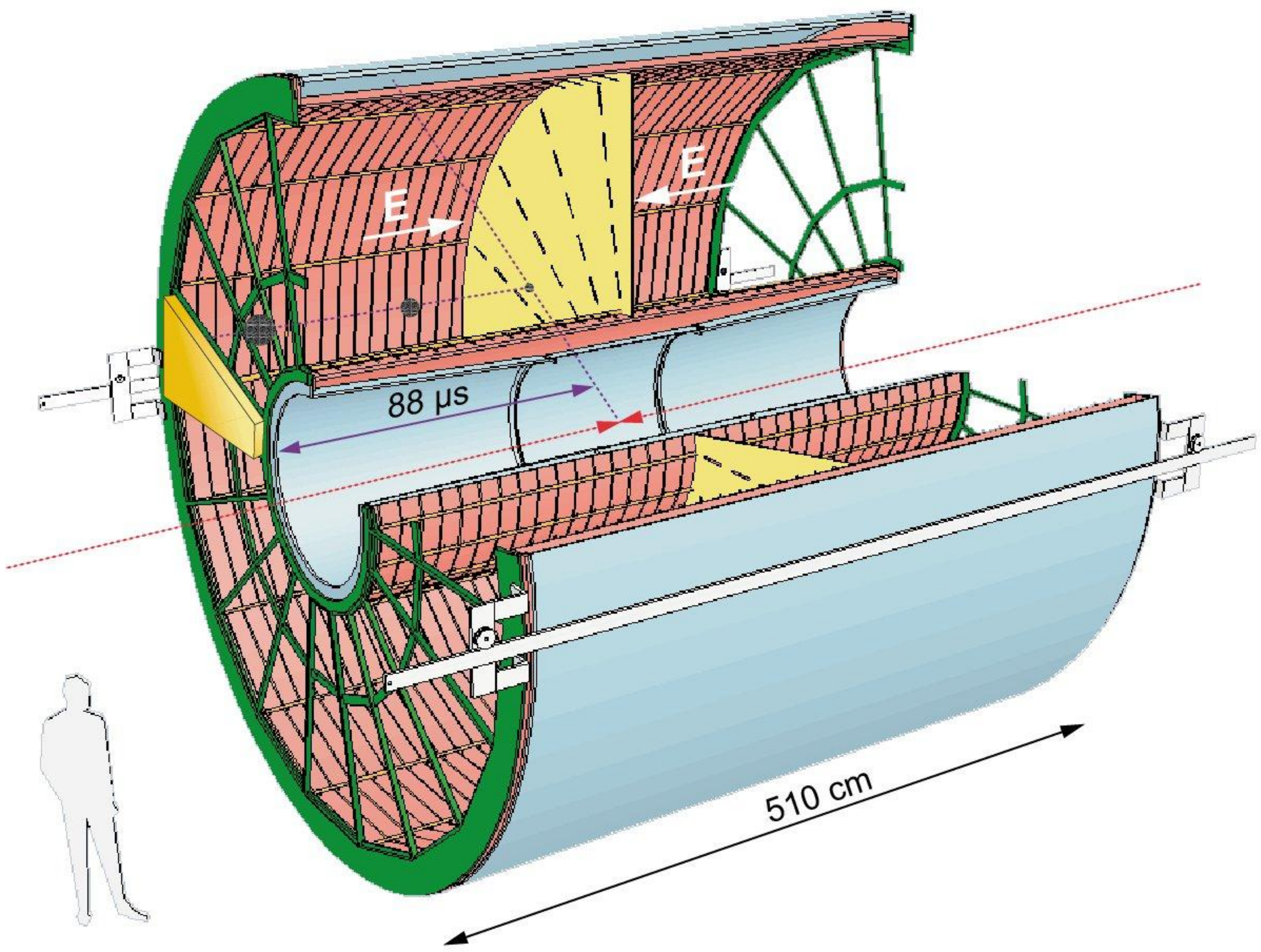
Diffusion: σ_t = 250 μm
Resolution: $\sigma \approx$ 0.2 mm

σ_p/p ~ 1% p; ε ~ 97%
$\sigma_{dE/dx}/(dE/dx)$ ~ 6%

Magnetic field: 0.5 T

Pad size: 5x7.5 mm^2 (inner)
6x15 mm^2 (outer)

Temperature control: 0.1 K
[also resistors ...]



Material: Cylinder build from composite material of airline industry (X_0= ~ 3%)

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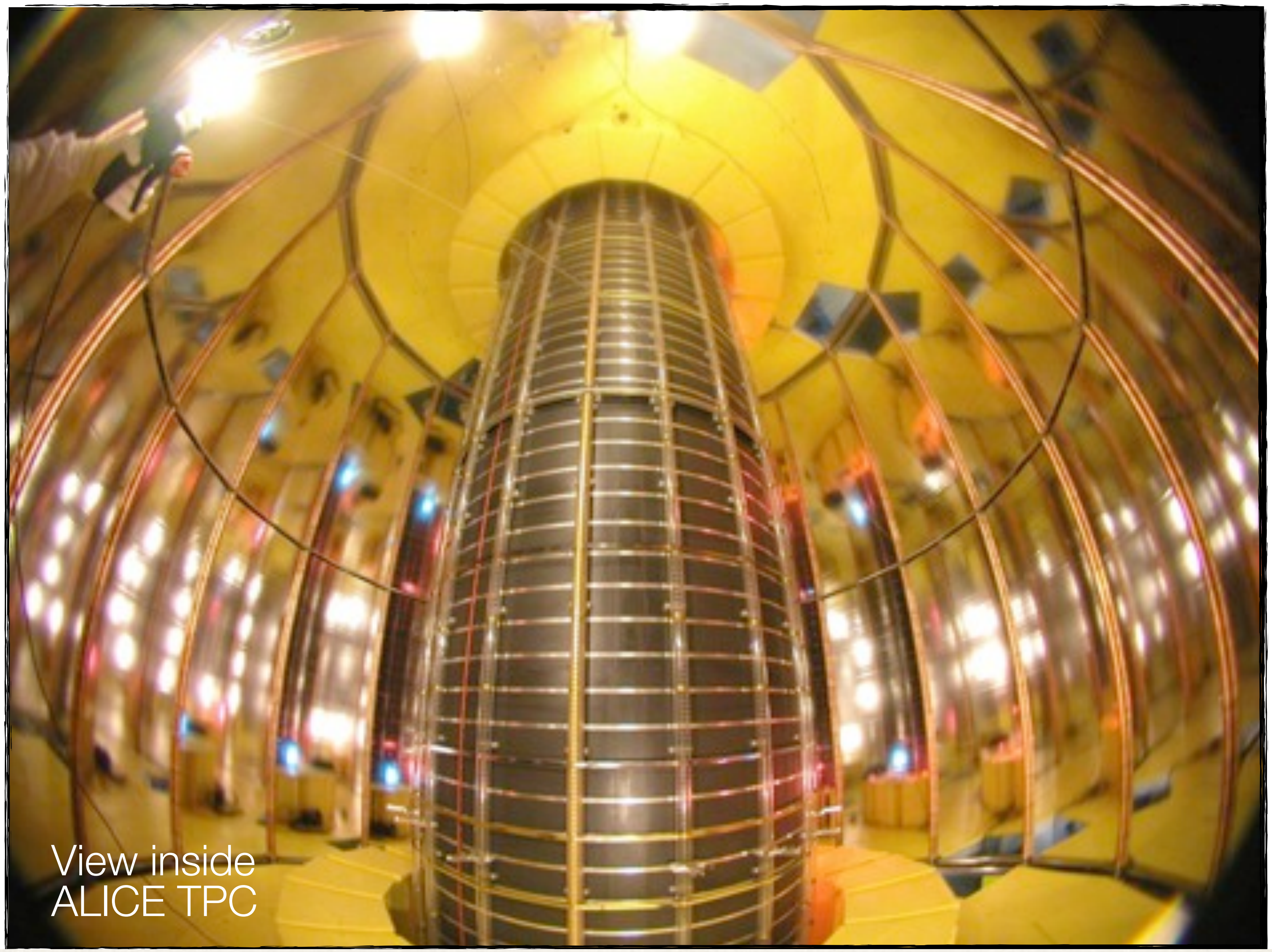
Time projection chamber (TPC)



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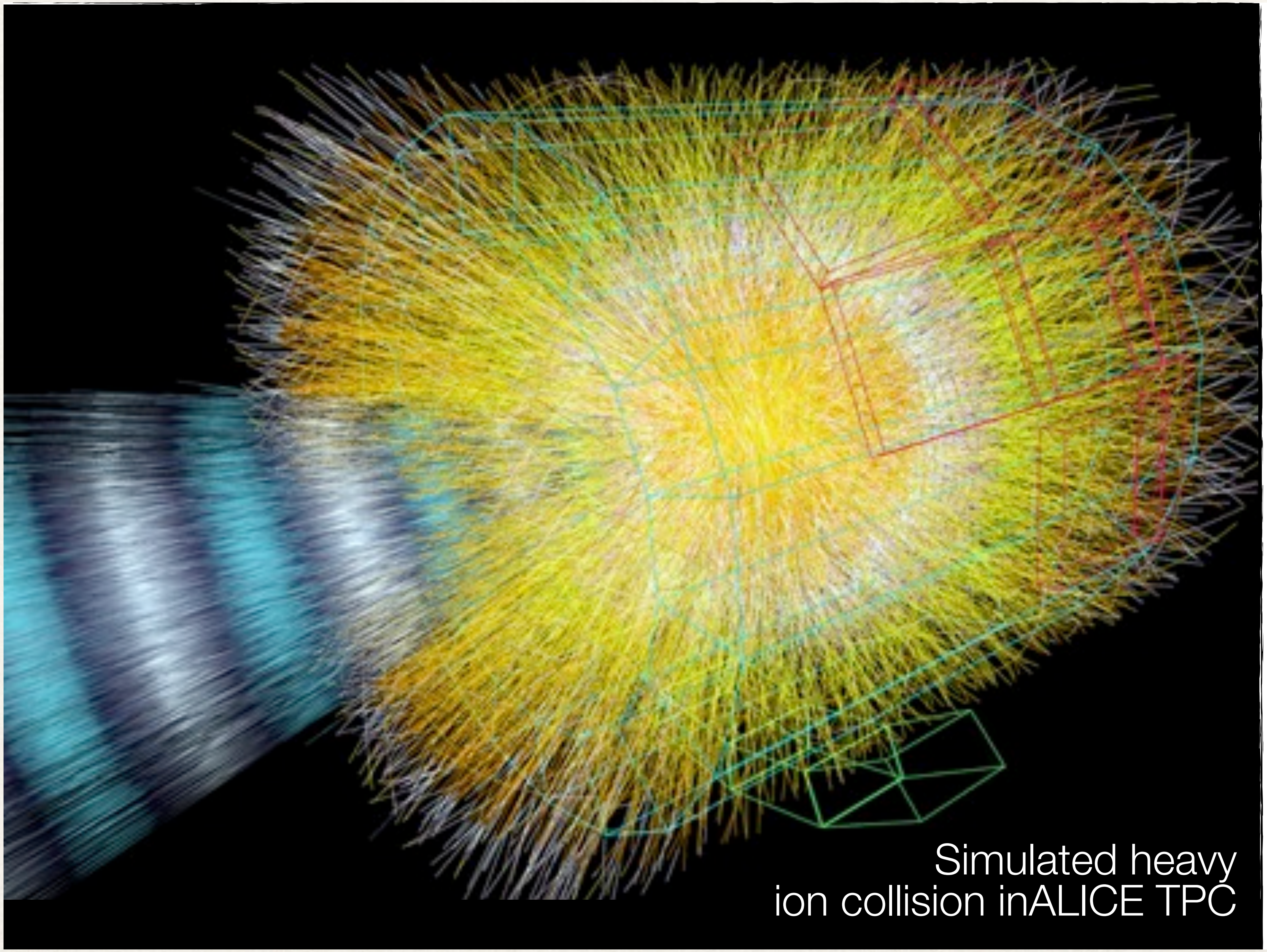
Time projection chamber (TPC)



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Envelhecimento das câmaras de fios

Avalanche formation can be considered as micro plasma discharge.

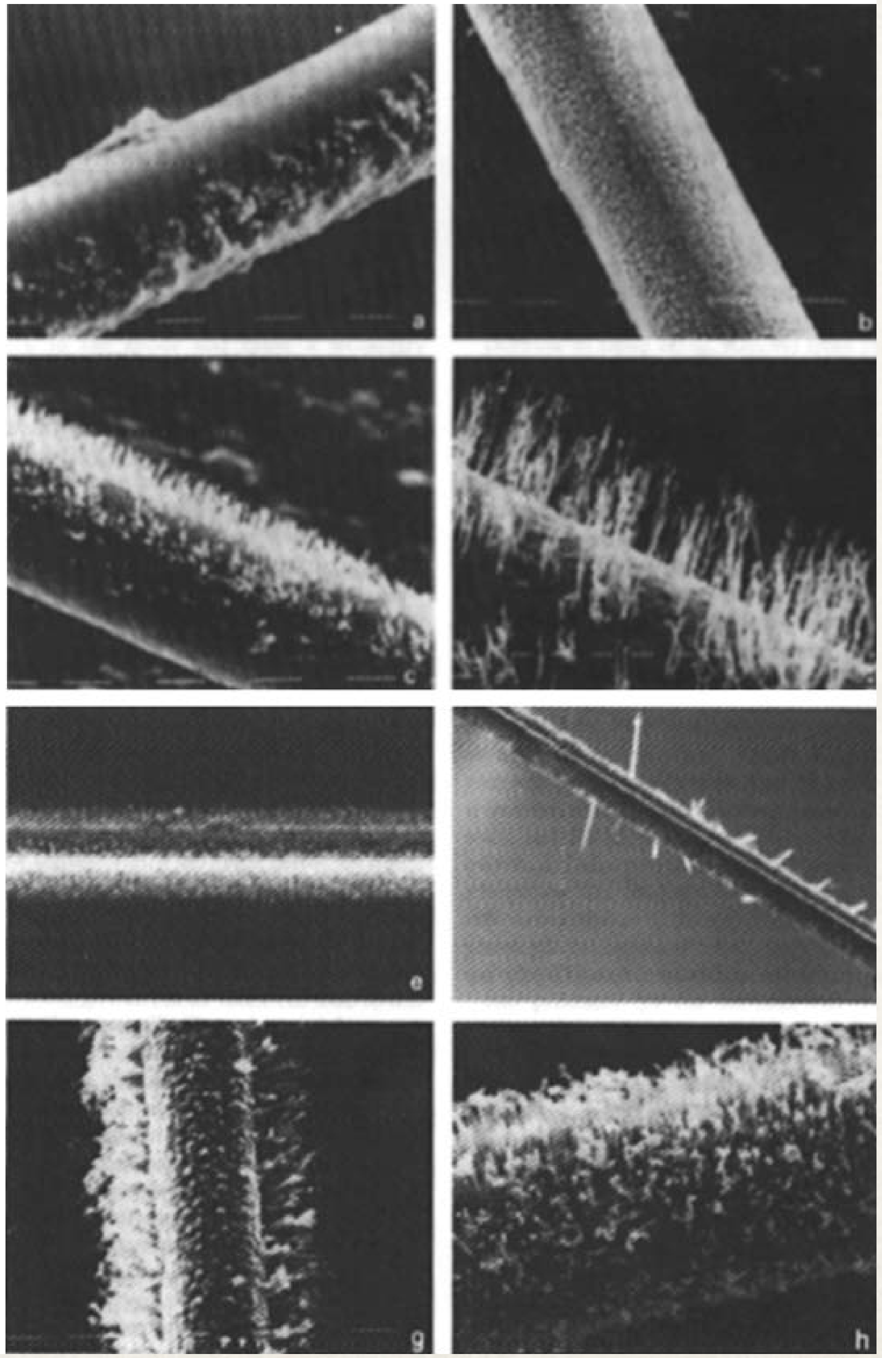
Consequences:

- Formation of radicals i.e. molecule fragments
- Polymerization yields long chains of molecules
- Polymers may be attached to the electrodes
- Reduction of gas amplification

Important:
Avoid unnecessary contamination ...

Harmful are ...

- Halogens or halogen compounds
- Silicon compounds
- Carbonates, halocarbons
- Polymers
- Oil, fat ...
- ....



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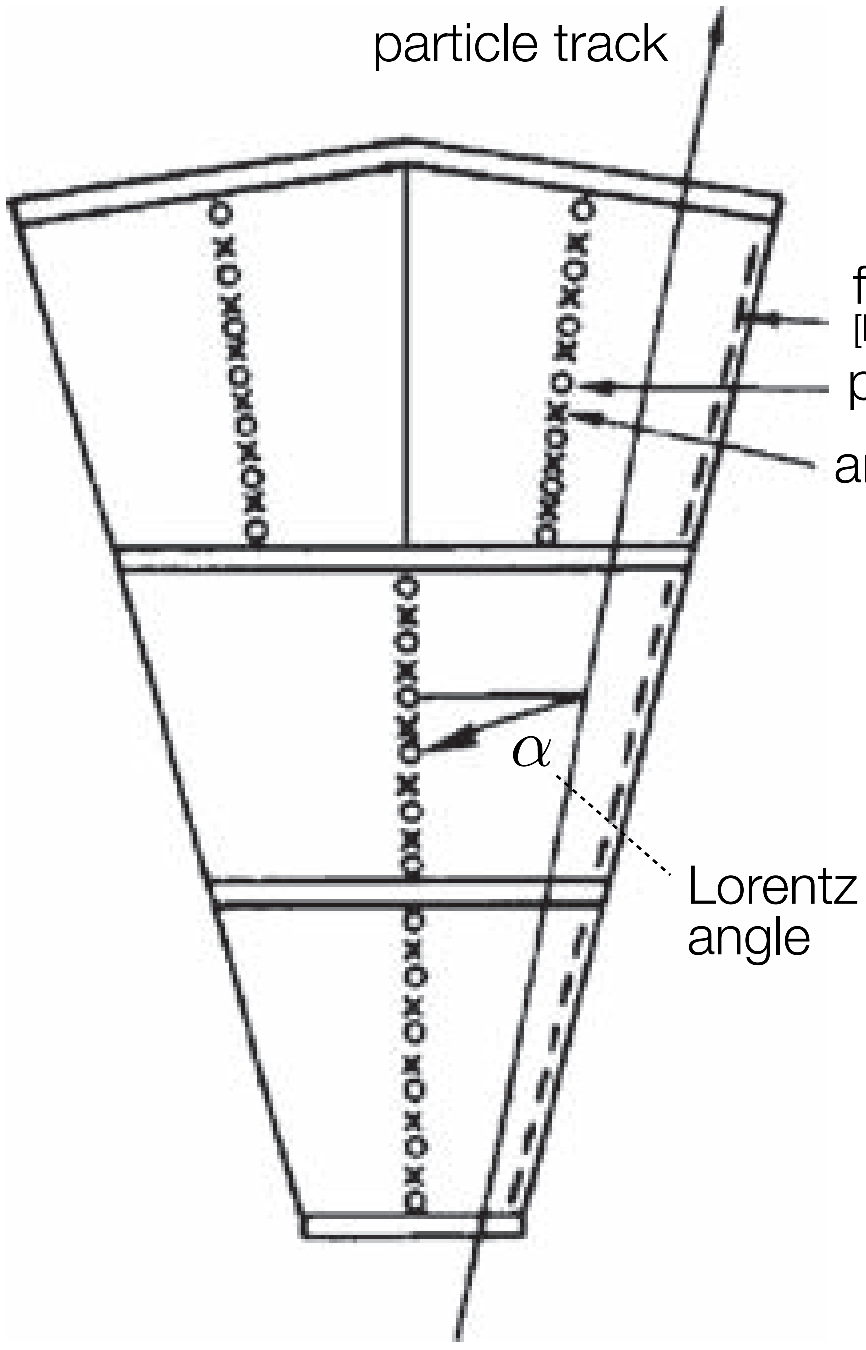
Jet drift chambers



Features:

Large number of sense wires
Large drift cells

Allows good dE/dx determination
[many measurements]

But: long drift times ...

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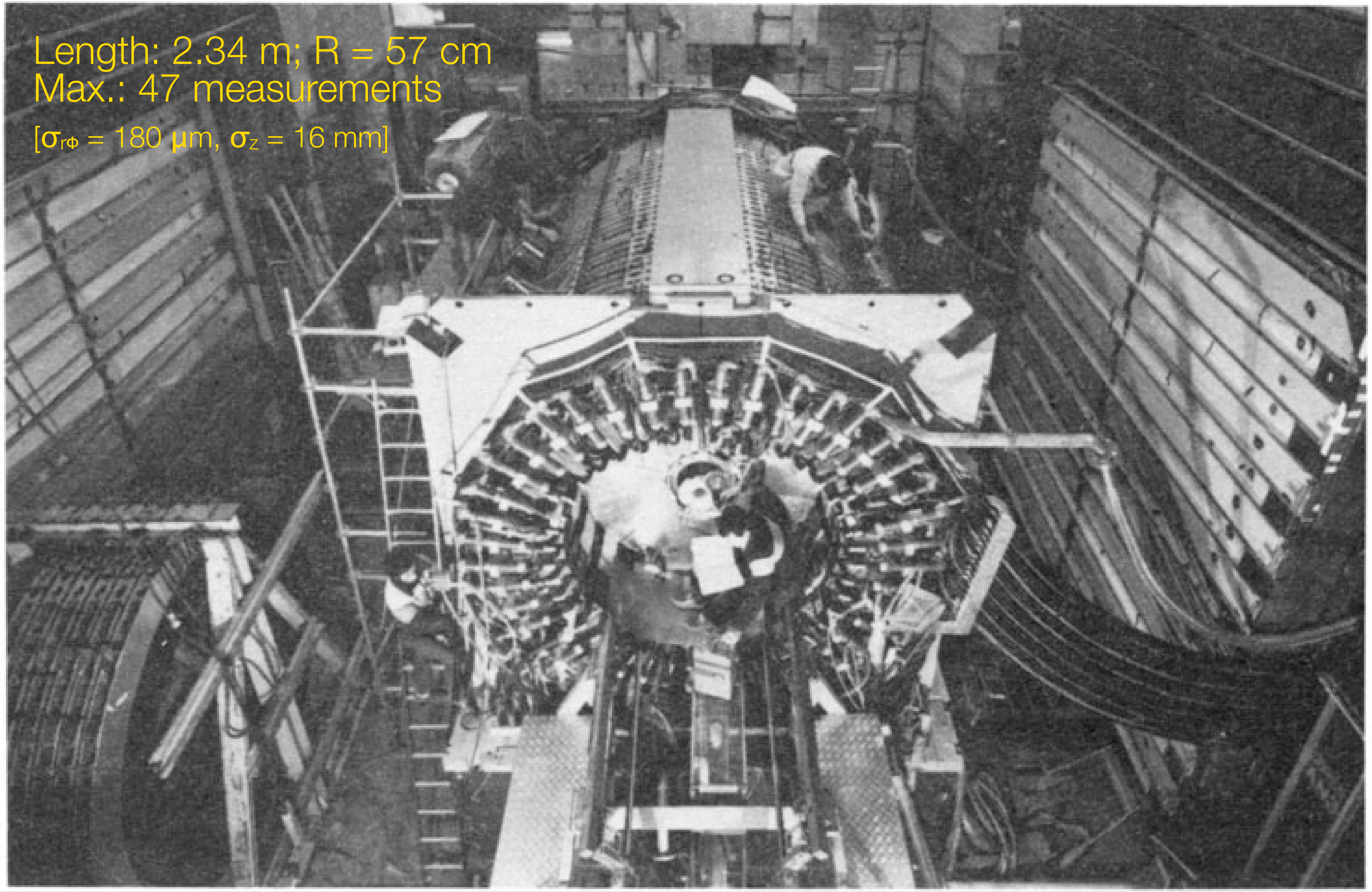
Jet drift chambers

Jet Drift Chambers – JADE



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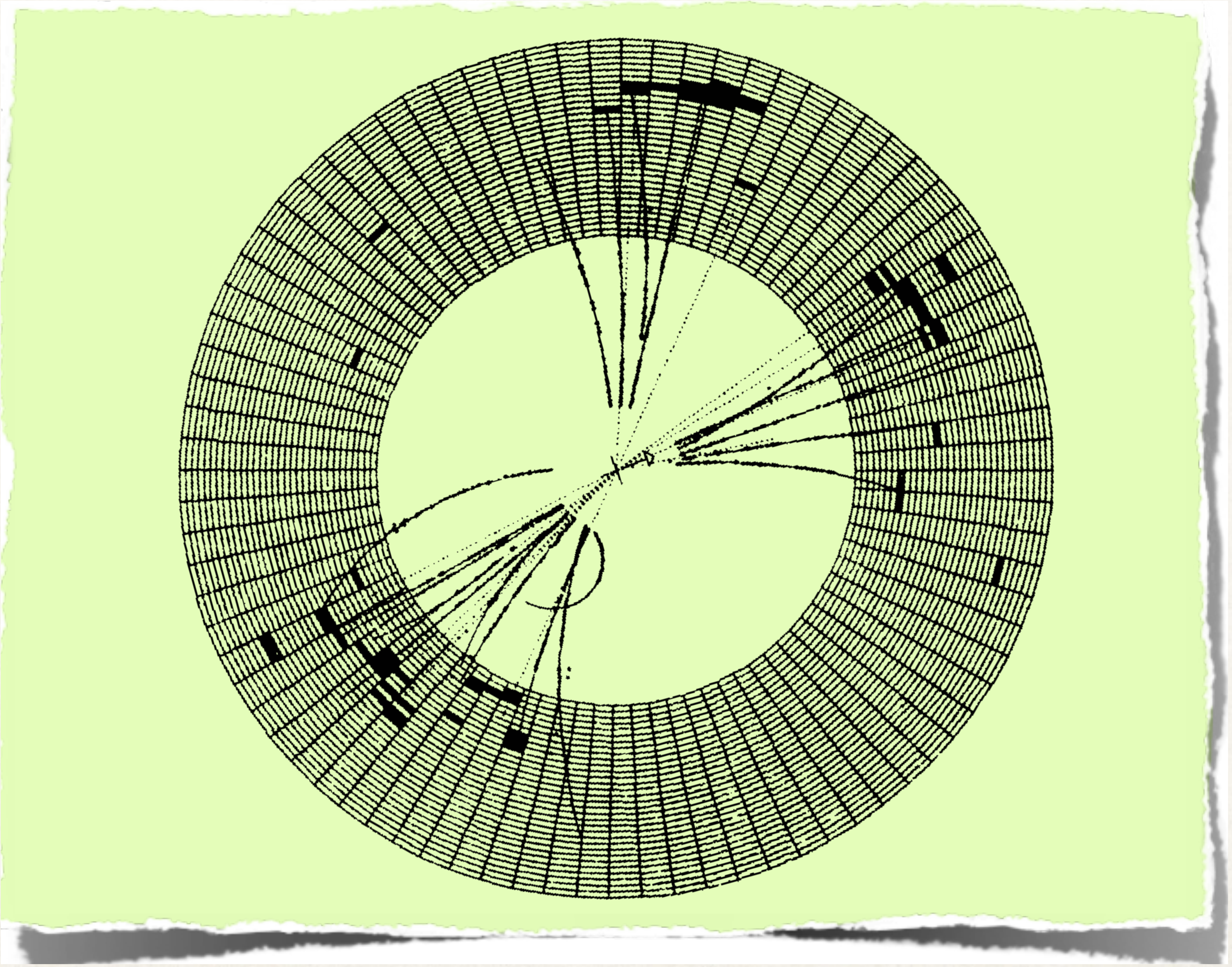
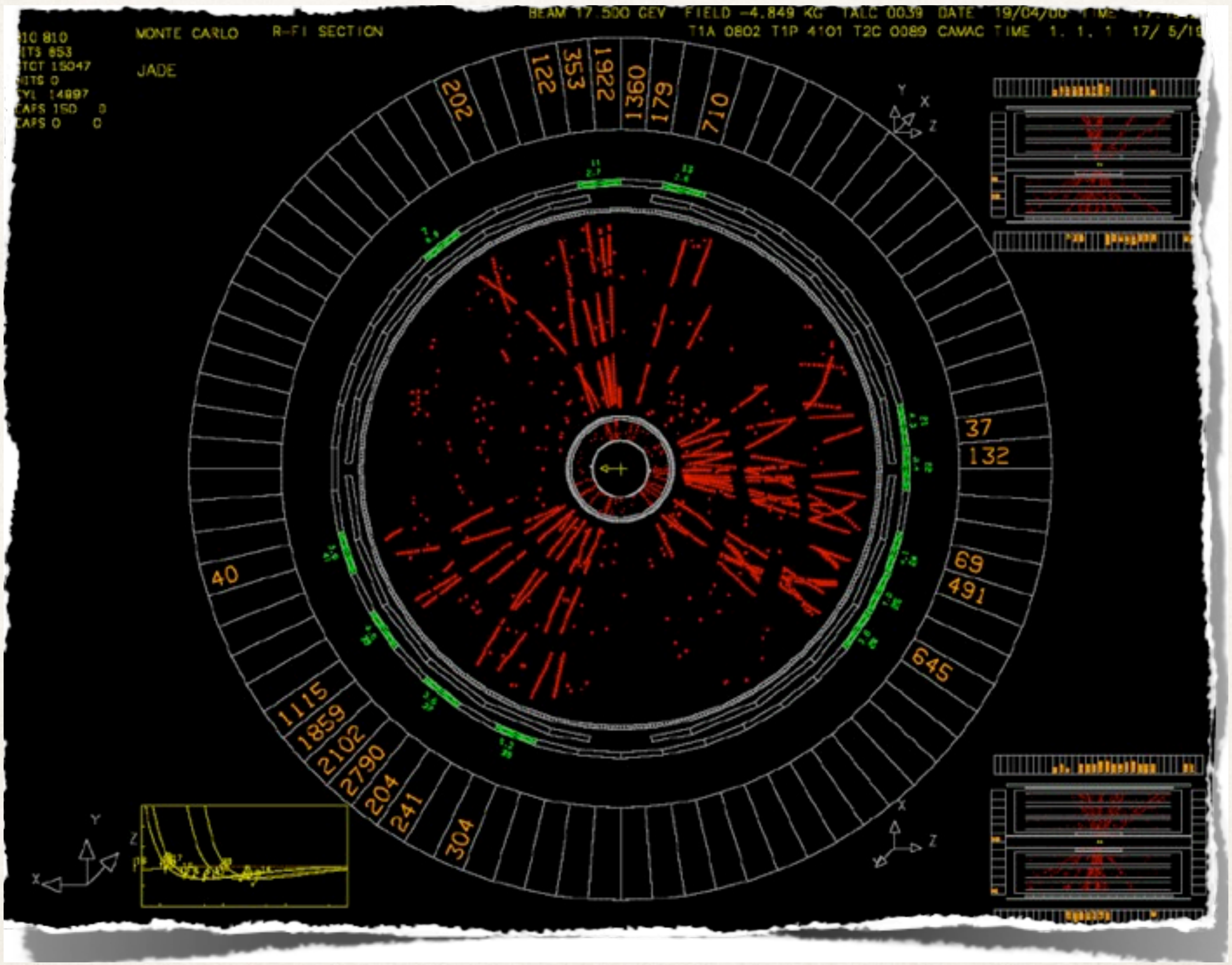
Jet drift chambers



http://cern.ch/amoraes

Jet drift chambers



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