Apparati Sperimentali

Lezione 4

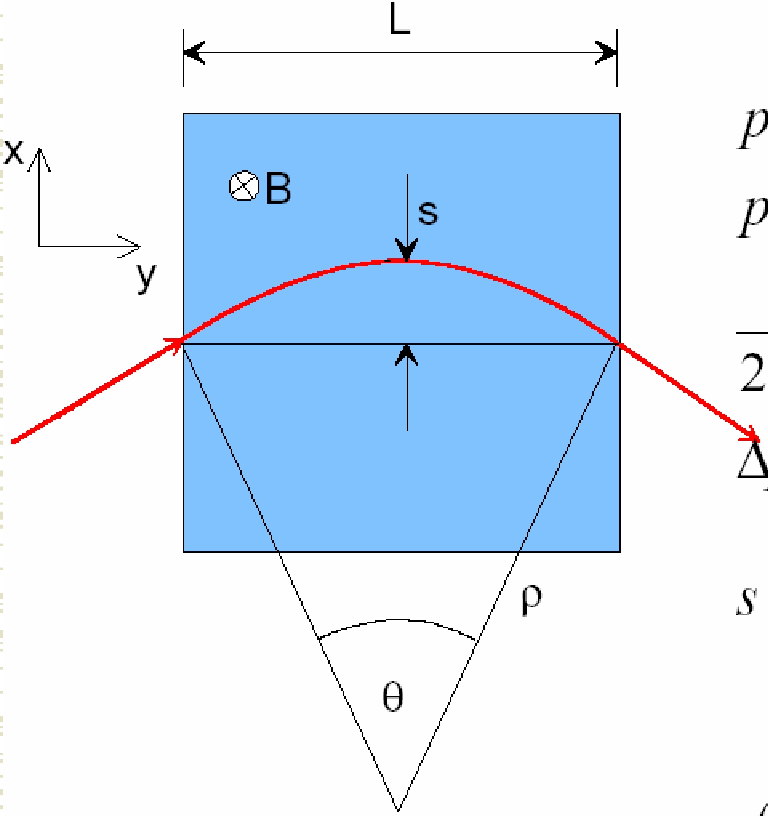
Tracciatura

Scintillatori e fibre

Misura delle proprieta’ delle particelle

- Carica
  - Segno:
    - Tracciatura in campo magnetico
  - Quantita’
    - Altezza d’impulso (ionizzazione o luce)
- Spin e vita media
  - Tracciatura (molto precisa)
- Massa
    - dalla misura dell’impulso con la tracciatura in campo magnetico +
    - energia con i calorimetri
    - Velocita’: TOF, Cherenkov, dE/dx

Misura dell'impulso



$$p_T = qB\rho$$

$$p_T\ (\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T\cdot m})$$

$$\frac{L}{2\rho} = \sin\theta/2 \approx \theta/2 \quad \rightarrow \quad \theta \approx \frac{0.3L\cdot B}{p_T}$$

$$\Delta p_T = p_T \sin\theta \approx 0.3L\cdot B$$

$$s = \rho(1-\cos\theta/2) \approx \rho\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{L^2B}{p_T}$$

$$s = x_2 - \frac{x_1 + x_3}{2} \quad \Rightarrow \quad \left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)\cdot 8p_T}{0.3\cdot BL^2}$$

Misura dell'impulso (2)

Per N punti equidistanti:

(R.L. Gluckstern, NIM 24 (1963) 381)

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$

(for N ≥ ≈10)

ex: p_T=1 GeV/c, L=1m, B=1T, $\sigma(x)$=200μm, N=10

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \approx 0.5\%$$

(s ≈ 3.75 cm)

A LEP: 0.1% p_T

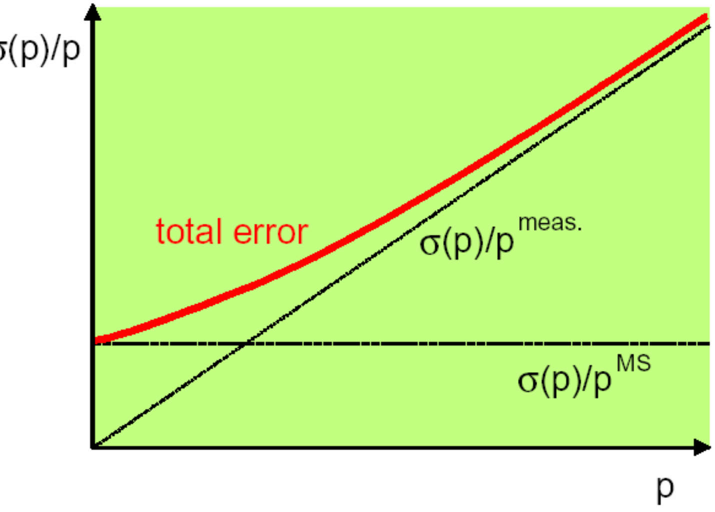
A LHC: 0.01% p_T (ad 1 TeV)

Effetto dello scattering multiplo

$$\Delta p^{MS} = p \sin\theta_0 \approx p \cdot 0.0136 \frac{1}{p} \sqrt{\frac{L}{X_0}}$$

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = \frac{\Delta p^{MS}}{p_T} = \frac{0.0136\sqrt{\frac{L}{X_0}}}{0.3BL} = 0.045 \frac{1}{B\sqrt{LX_0}}$$

Indipendente da p!



X_0

110 m per Ar (gas)
8.9 cm per Al
0.56 cm per Pb

Es: Ar (X_0=110 m), L=1m, B=1T

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} \approx 0.5\%$$

Misura delle coordinate

- Segnali di ionizzazione
  - Contatori Geiger-Müller
  - MWPC (Multi-Wire Proportional Chambers)
  - TPC (Time Projection Chamber)
  - Rivelatori al silicio
- Luce di scintillazione
  - Fibre scintillanti

Rivelatori a gas

$$n_{total} = \frac{\Delta E}{W_i} = \frac{\frac{dE}{dx}\Delta x}{W_i}$$

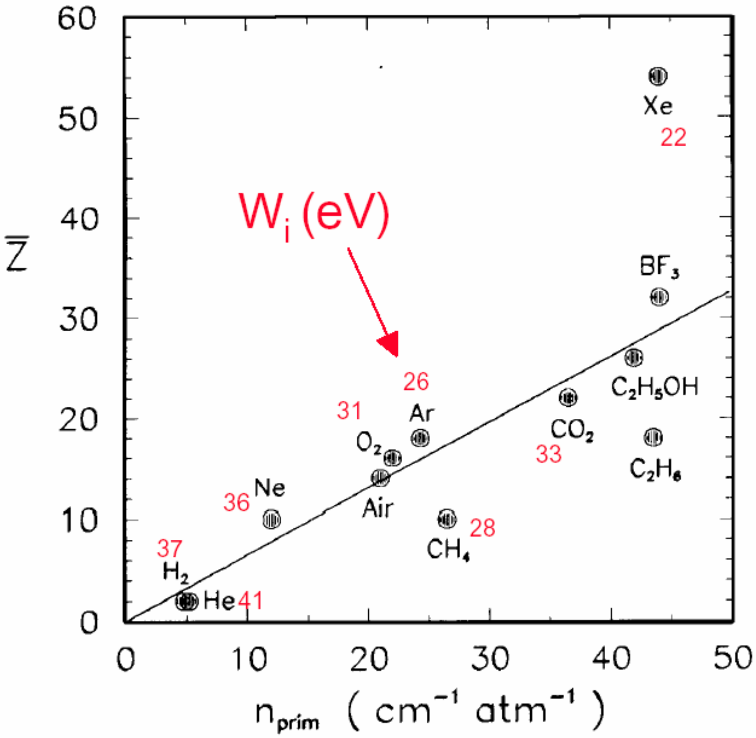
$$n_{total} \approx 3\ldots4 \cdot n_{primary}$$

total number of created electron-ion pairs.

ΔE = total energy loss

W_i = effective <energy loss>/pair

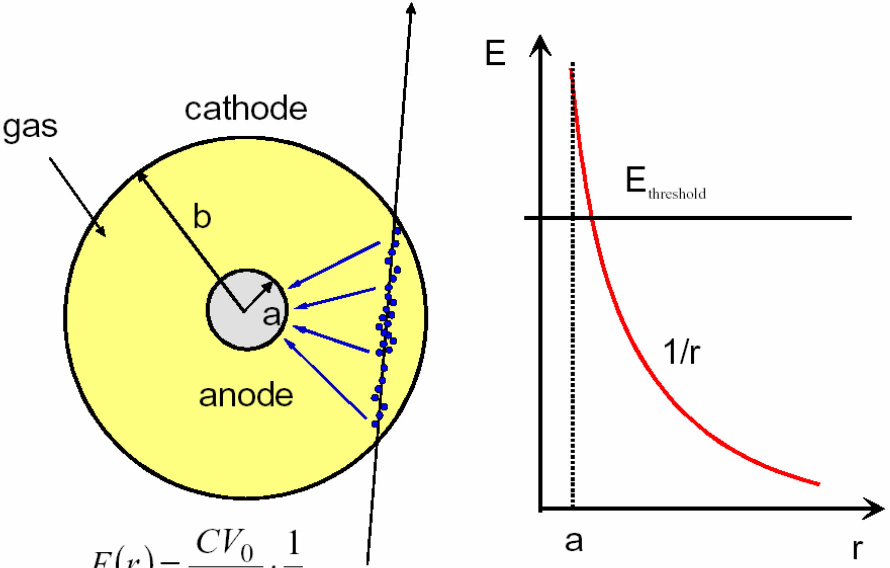
Number of primary electron/ion pairs in frequently used (detector) gases.



(Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific,1992)

Contatori proporzionali

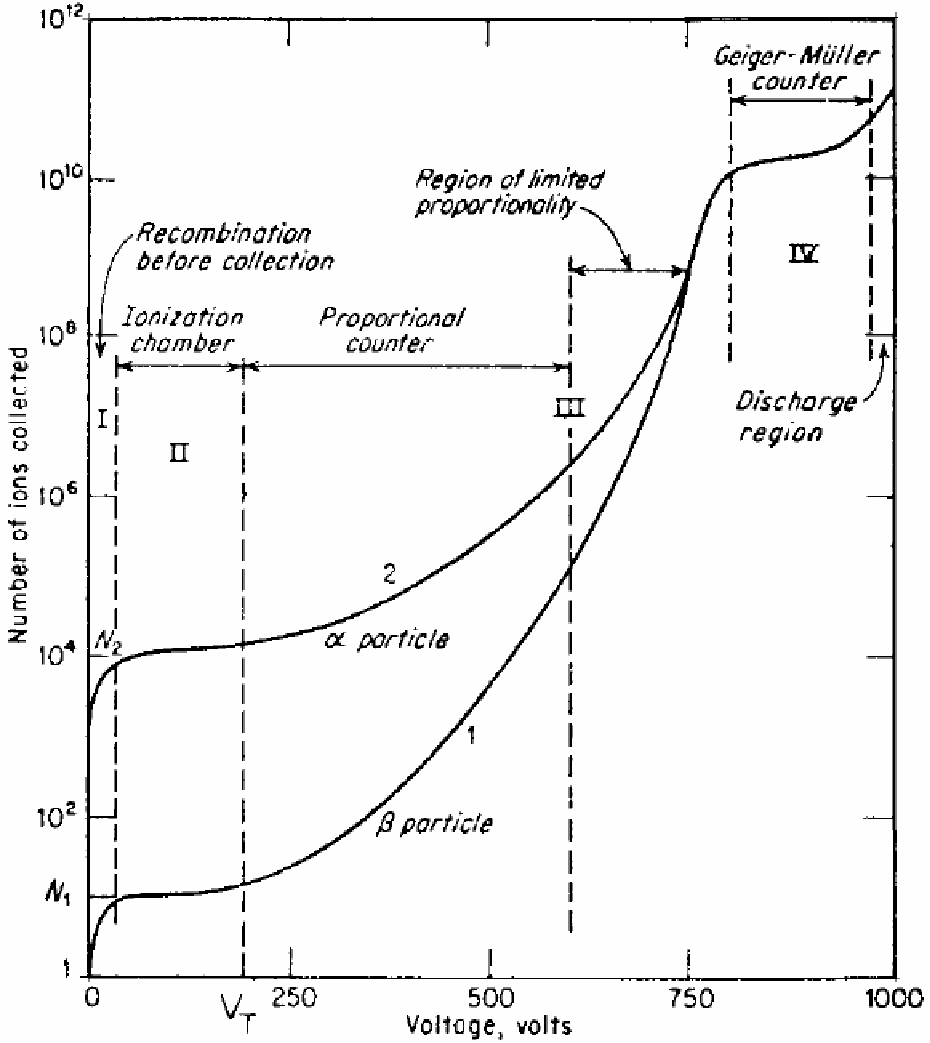
- Poche centinaia di elettroni sono troppo pochi da rivelare
- Il rumore elettronico spesso e` dello stesso ordine di grandezza ed anche piu`
- Amplificazione del segnale direttamente sul detector:
  - Meccanismo di moltiplicazione a valanga



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

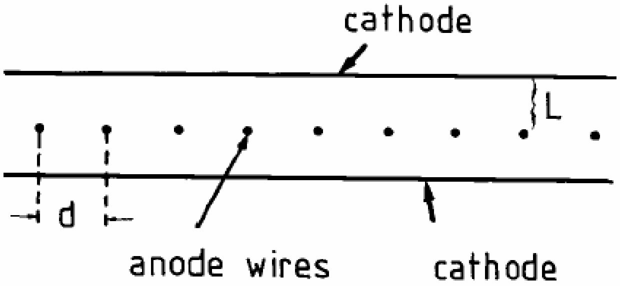
$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a}$$

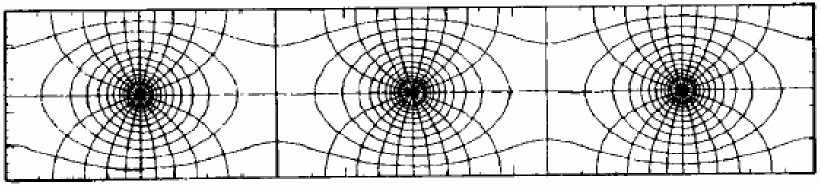
C = capacitance / unit length

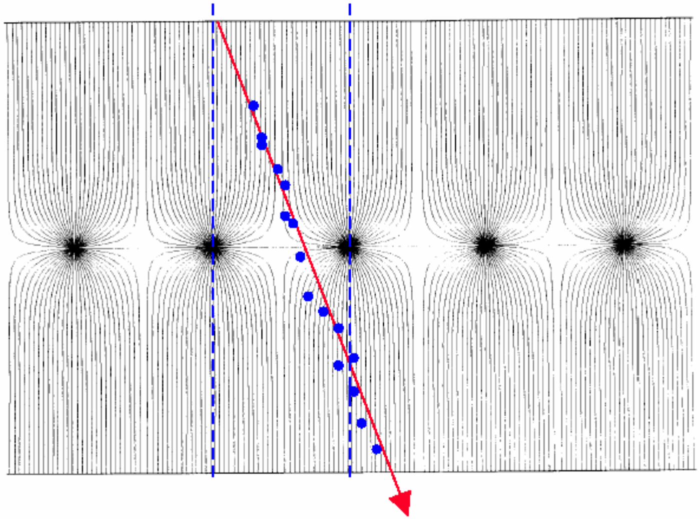

10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
N_1
1
N_2
Number of ions collected
0
V_T
250
500
750
1000
Voltage, volts
Geiger-Müller counter
Region of limited proportionality
Recombination before collection
Ionization chamber
Proportional counter
I
II
III
IV
Discharge region
2
α particle
1
β particle

Multi wire proportional chamber (MWPC)

(G. Charpak et al. 1968, Nobel prize 1992)



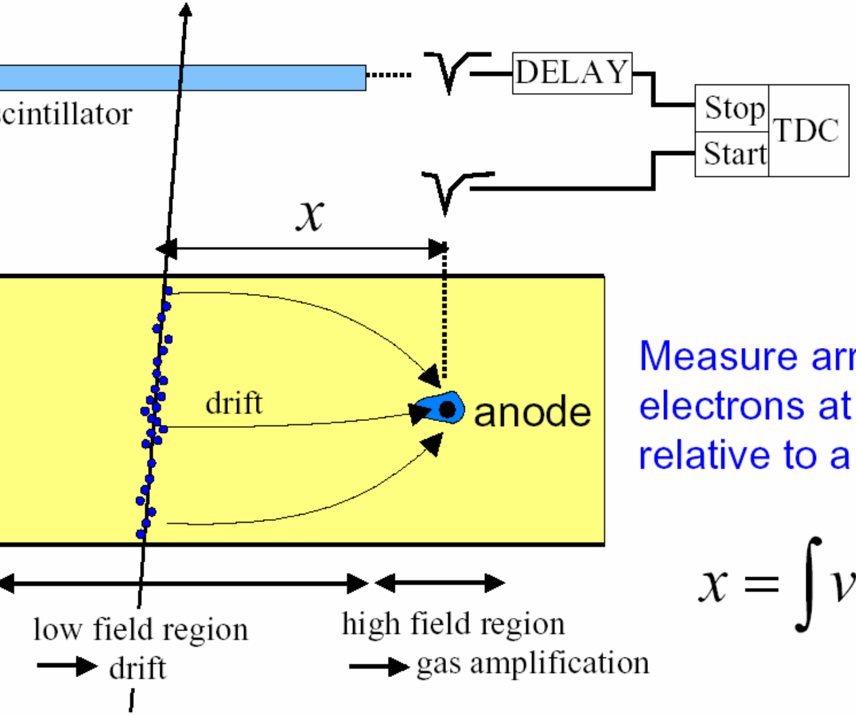

field lines and equipotentials around anode wires



Typical parameters:
L=5mm, d=1mm,
a_{wire}=20mm.

Normally digital readout:
spatial resolution limited to $\sigma_x \approx \frac{d}{\sqrt{12}}$ (d=1mm, σ_x=300 μm)

Camere a deriva



Measure arrival time of electrons at sense wire relative to a time t_0.

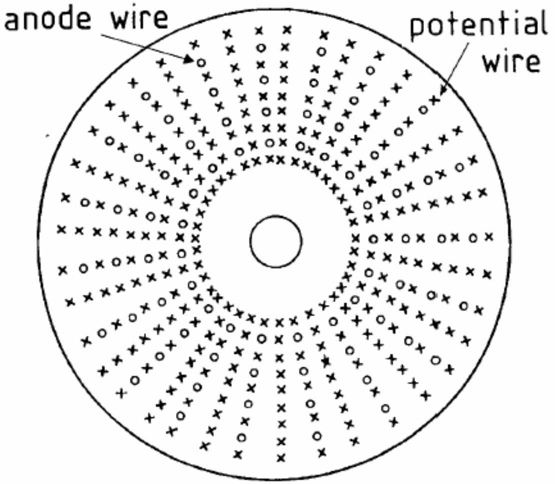
$$x = \int v_D(t)dt$$

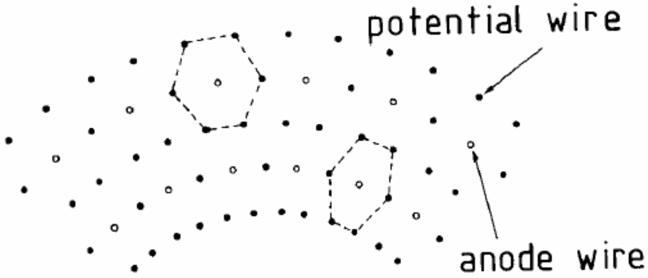
Hanno il vantaggio di avere meno fili, meno elettronica, e meno strutture di supporto rispetto alle MWPC

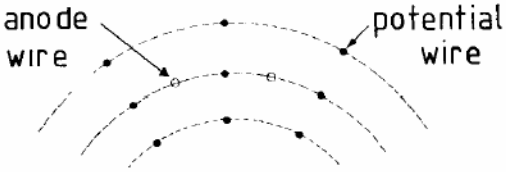
La risoluzione non e' limitata dalla dimensione della cella

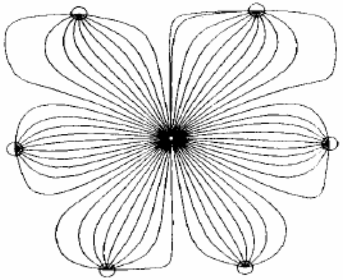
Se si controlla la miscela di gas si ottengono buone risoluzioni ≥50 micron

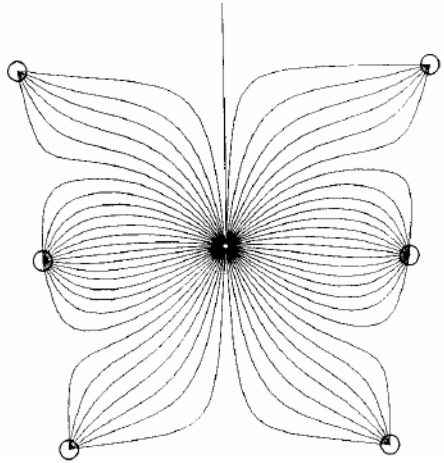
Various geometries of cylindrical drift chambers





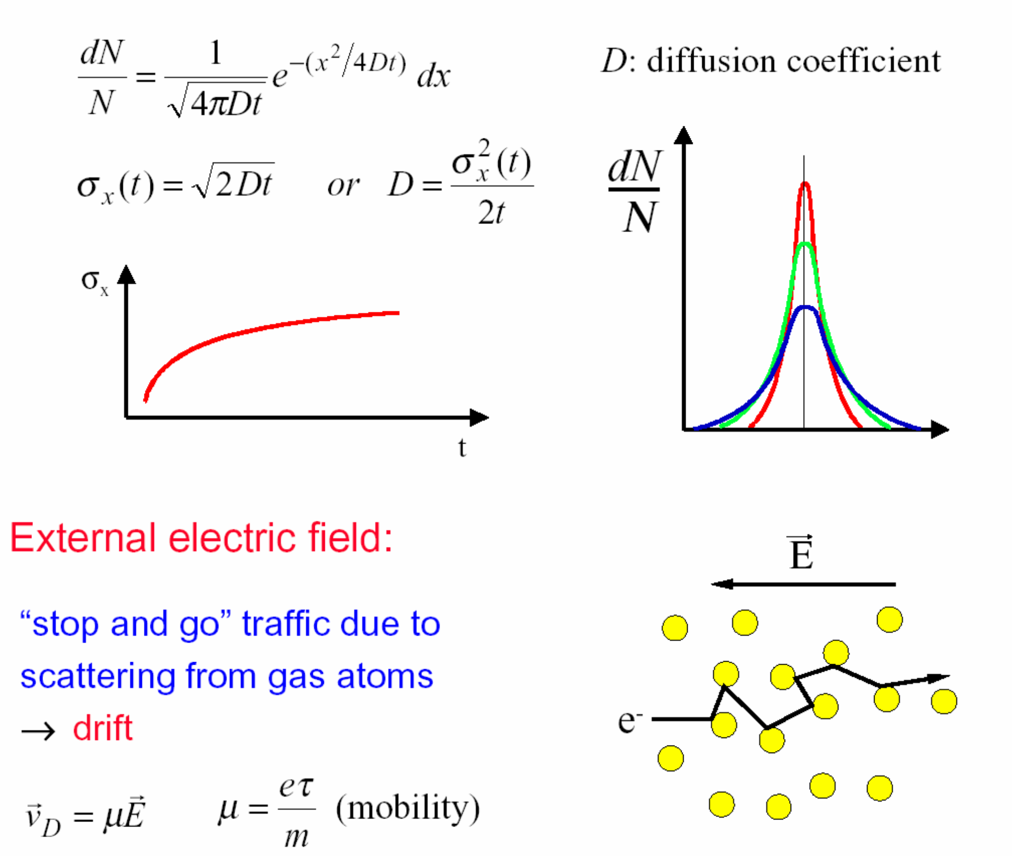






Diffusione

In assenza di campo elettrico gli elettroni e gli ioni diffondono



$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}}\, e^{-(x^2/4Dt)}\, dx$$

D: diffusion coefficient

$$\sigma_x(t) = \sqrt{2Dt} \qquad or \qquad D = \frac{\sigma_x^2(t)}{2t}$$

External electric field:

"stop and go" traffic due to scattering from gas atoms

→ drift

$$\vec{v}_D = \mu \vec{E} \qquad \mu = \frac{e\tau}{m} \quad \text{(mobility)}$$

Moto in un campo (E,B)

$$\frac{\vec{v}_D}{\tau} + \frac{e\vec{B}\times\vec{v}_D}{m_e} = \frac{eE}{m_e}$$

$$\vec{v}_D = \frac{\mu E}{1+\omega^2\tau^2}\left[\vec{E} + \frac{\vec{E}\times\vec{B}}{|\vec{B}|}\omega\tau + \frac{(\vec{E}\cdot\vec{B})\cdot\vec{B}}{|\vec{B}|^2}\omega^2\tau^2\right]$$

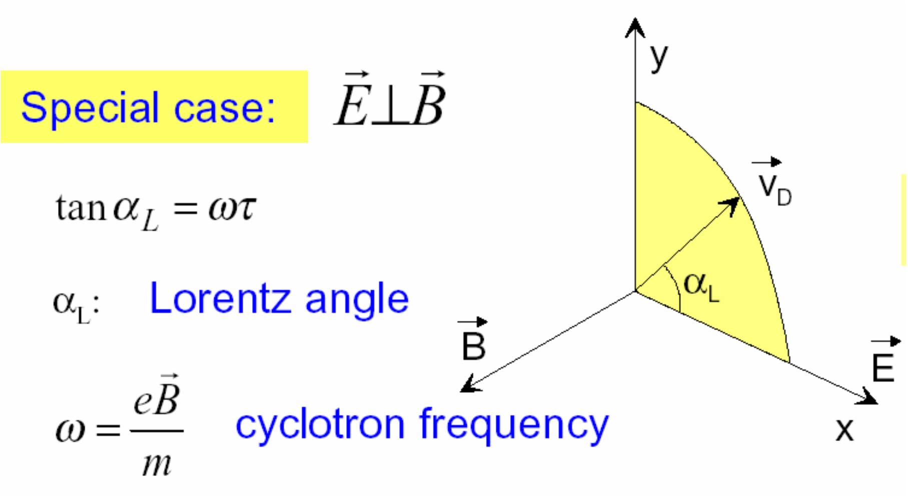
$$\omega = \frac{e|\vec{B}|}{m_e}$$ (Frequenza di ciclotrone)

τ = tempo medio di collisione

$\omega\tau \ll 1$ e^- seguono E
$\omega\tau \gg 1$ e^- seguono B

Velocita` tipica per elettroni nei gas ~ 5 cm/μs

Per gli ioni 1000 volte minore



Special case: $\vec{E}\perp\vec{B}$

$\tan\alpha_L = \omega\tau$

α_L: Lorentz angle

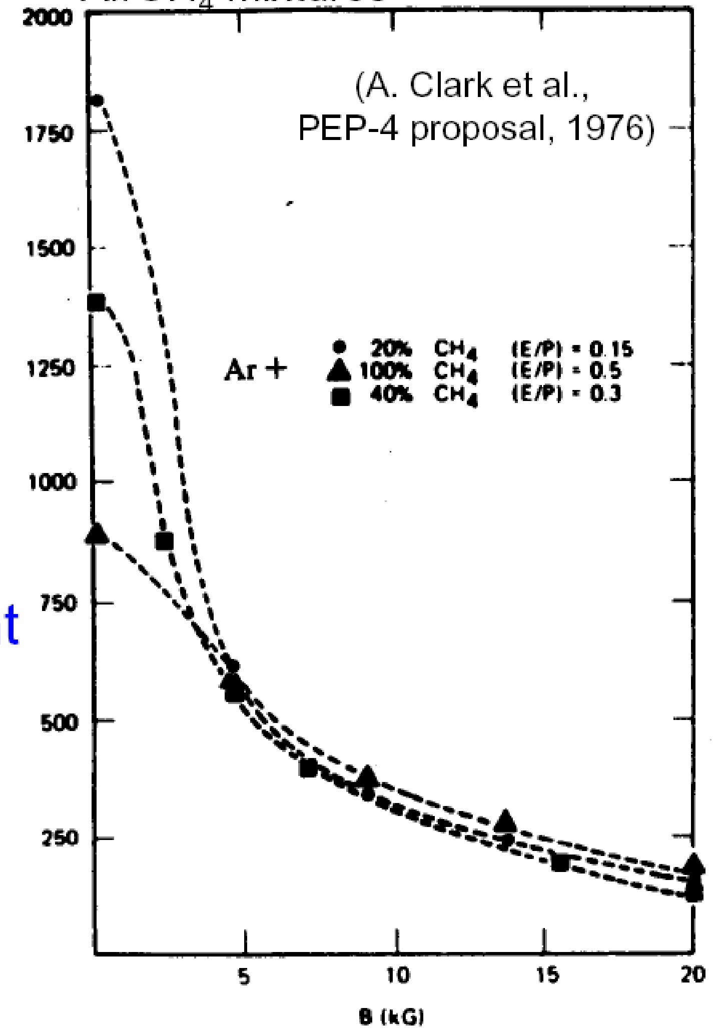
$\omega = \frac{e\vec{B}}{m}$ cyclotron frequency

Special case: $\vec{E} \parallel \vec{B}$

The longitudinal diffusion (along B-field) is unchanged.
In the transverse projection the electrons are forced on circle segments with the radius v_T/ω.
The transverse diffusion coefficient appears reduced

$$D_T(B) = \frac{D_0}{1+\omega^2\tau^2}$$

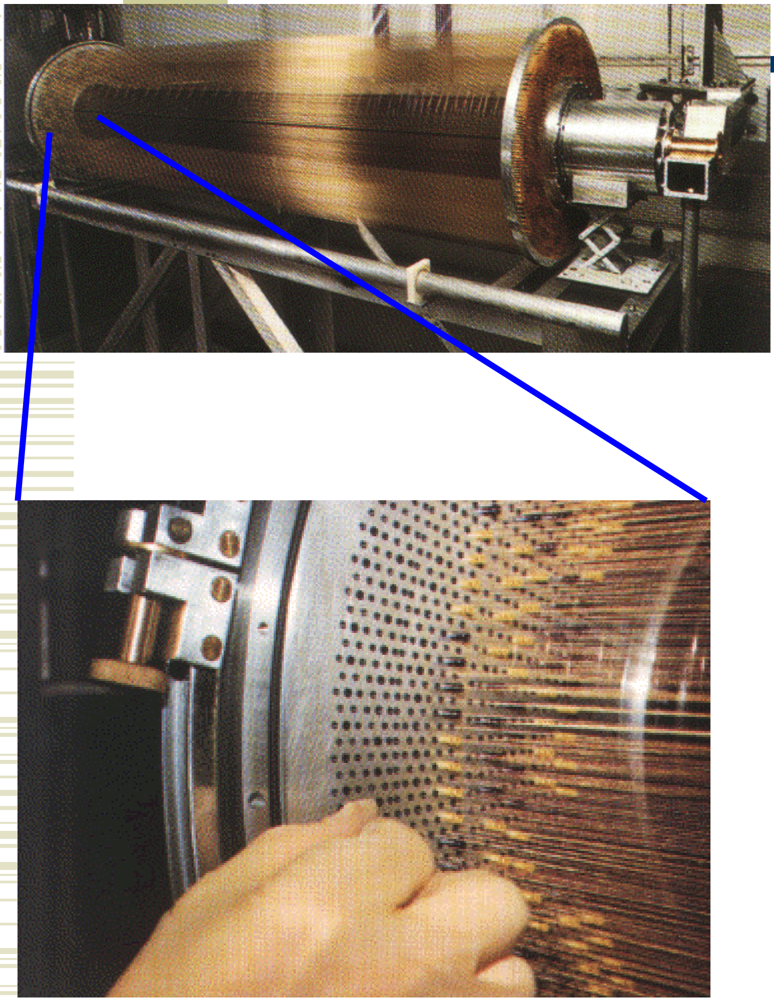
Transverse diffusion σ (μm) for a drift of 15 cm in different Ar/CH_4 mixtures


(A. Clark et al., PEP-4 proposal, 1976)

Esempi

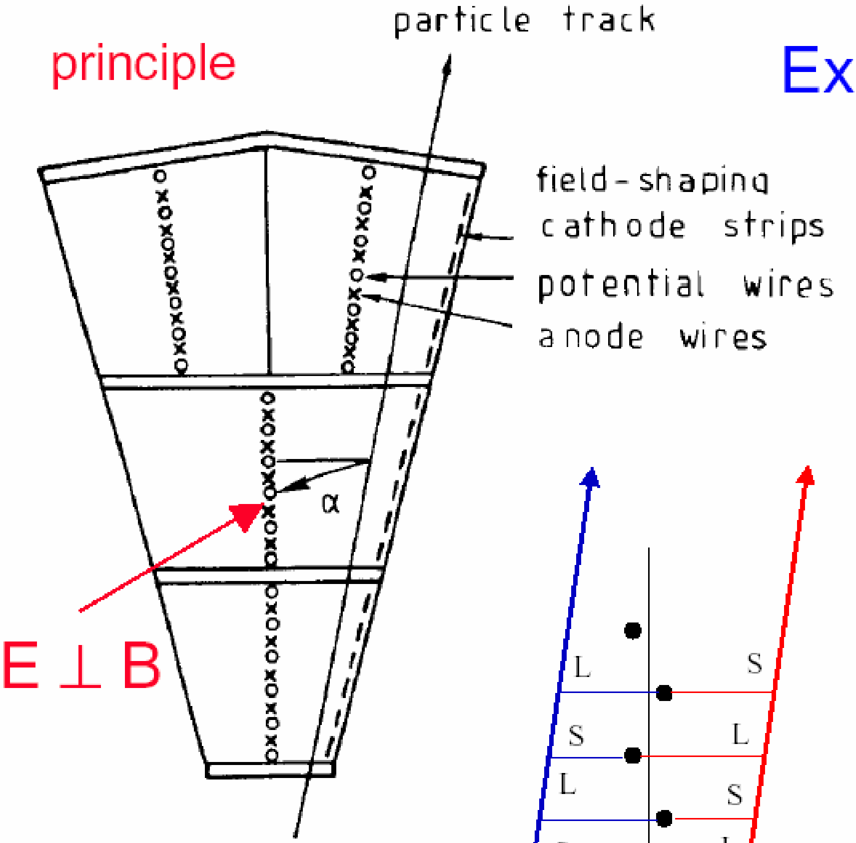
ITC (ALEPH)

Inner Tracking Chamber



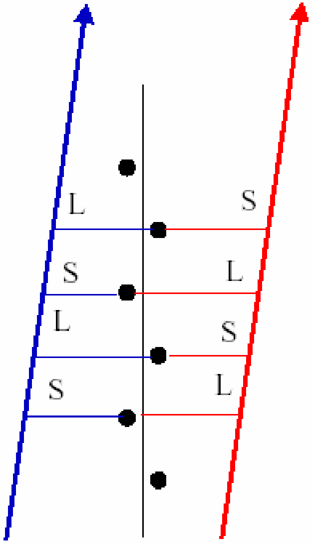
Jet chambers: Optimized for maximum number of measurements in radial direction

principle



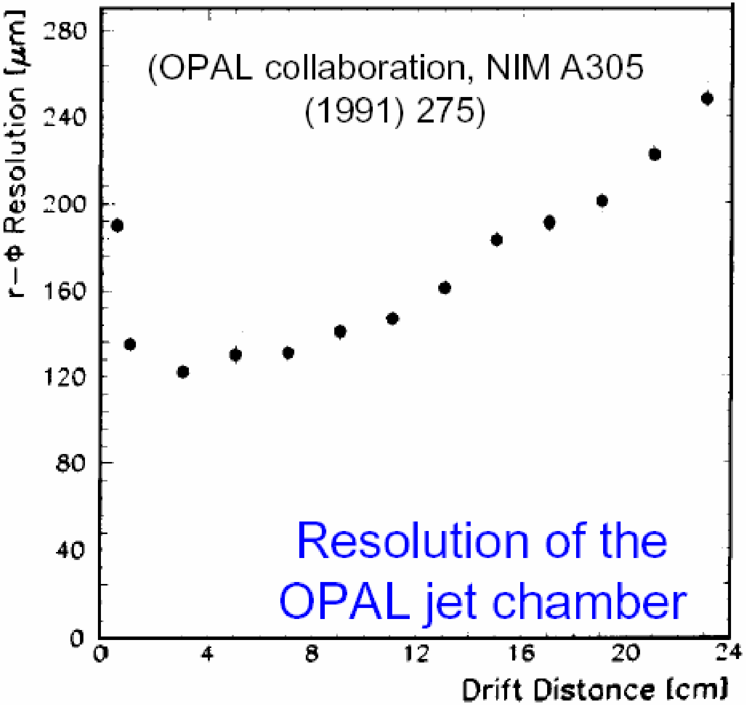
E ⊥ B

Resolve left/right ambiguities



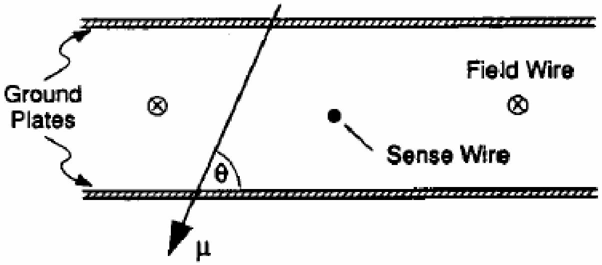
Example: OPAL Jet chamber

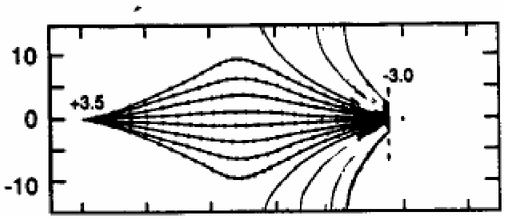
Ø=3.7m, L=4m, 24 sectors à 159 sense wires (±100 µm staggered). 3 cm < l_{drift} < 25 cm

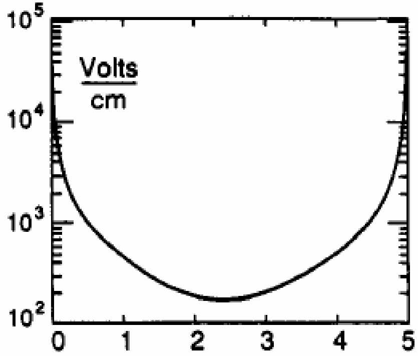


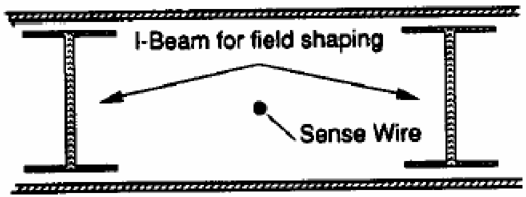
(OPAL collaboration, NIM A305 (1991) 275)

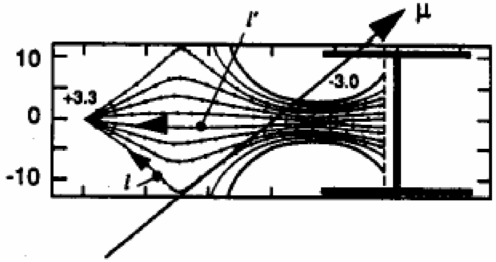
Resolution of the OPAL jet chamber

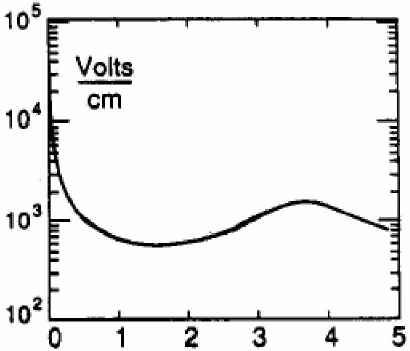

Ground Plates
Field Wire
Sense Wire
θ
μ

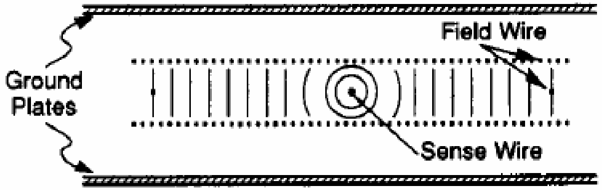

10
0
-10
+3.5
-3.0

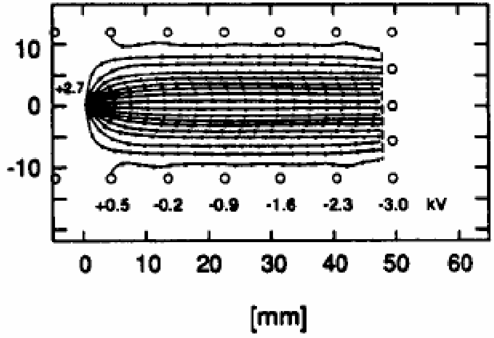

10^5
10^4
10^3
10^2
Volts/cm
0
1
2
3
4
5

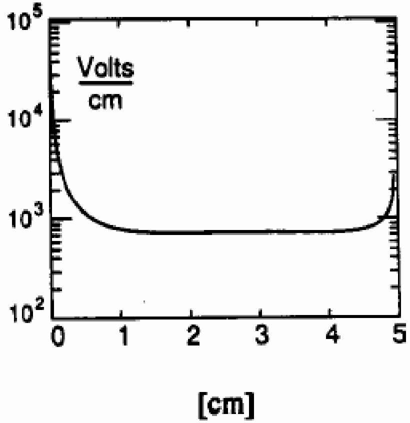

I-Beam for field shaping
Sense Wire


10
0
-10
+3.3
-3.0
l'
l
μ

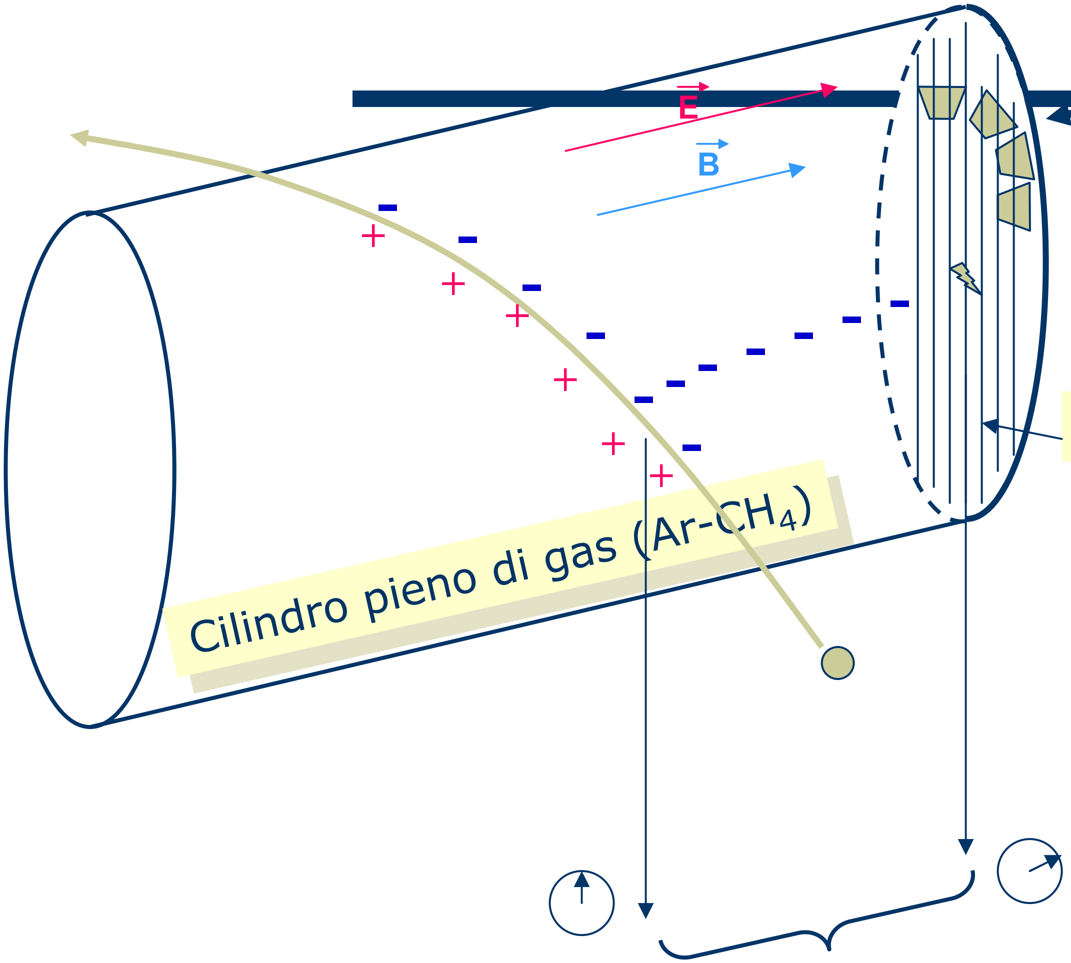

10^5
10^4
10^3
10^2
Volts/cm
0
1
2
3
4
5


Ground Plates
Field Wire
Sense Wire


10
0
-10
+2.7
+0.5
-0.2
-0.9
-1.6
-2.3
-3.0
kV
0
10
20
30
40
50
60
[mm]


10^5
10^4
10^3
10^2
Volts/cm
0
1
2
3
4
5
[cm]

La Time Projection Chamber (TPC)



MWPC

fornisce r,ϕ

Fili anodici

Cilindro pieno di gas (Ar-CH$_4$)

$z = v_{drift}\, t$

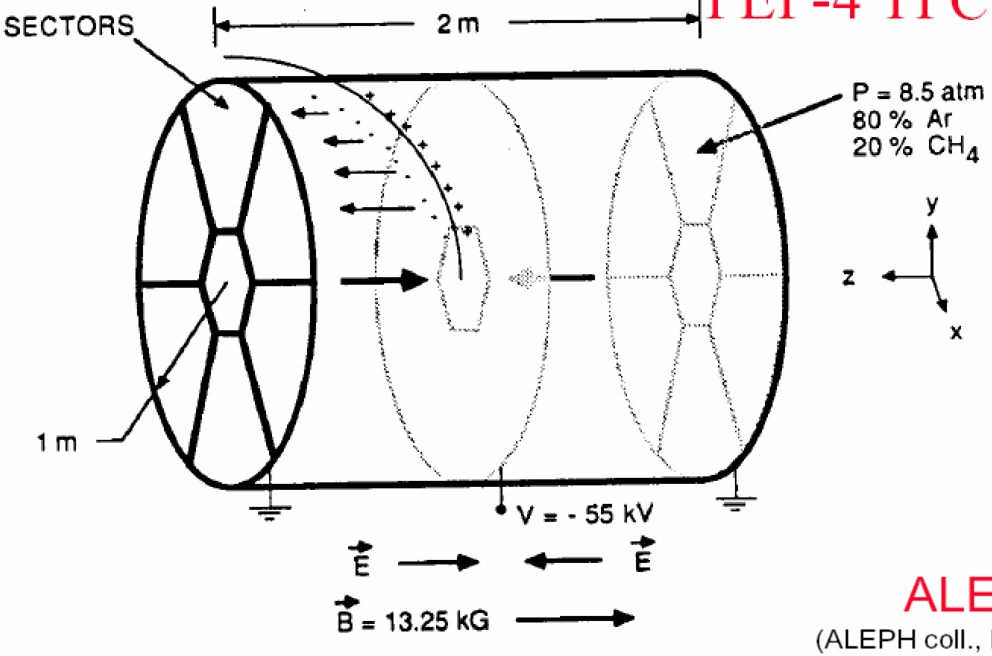
Time Projection Chamber → full 3-D track reconstruction

- x-y from wires and segmented cathode of MWPC
- z from drift time
- in addition dE/dx information

Diffusion significantly reduced by B-field.

Requires precise knowledge of v_D → LASER calibration + p,T corrections

PEP-4 TPC

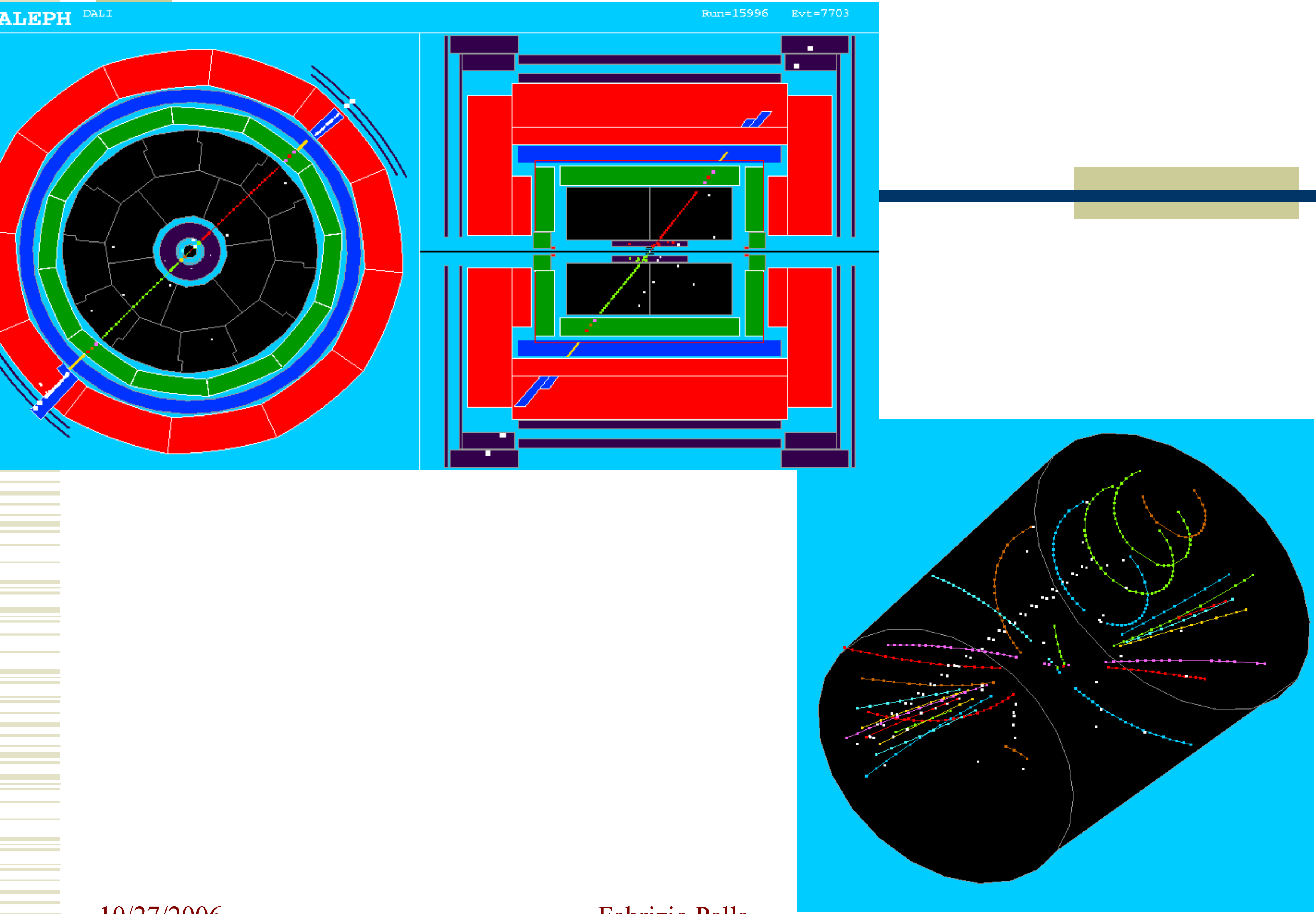


ALEPH TPC

(ALEPH coll., NIM A 294 (1990) 121,
W. Atwood et. Al, NIM A 306 (1991) 446)

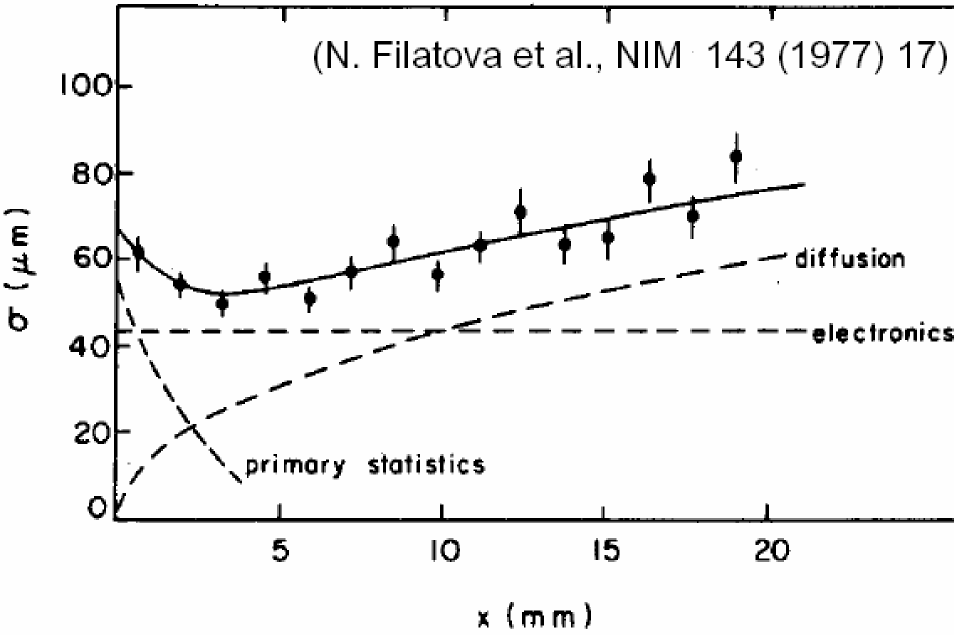
Ø 3.6M, L=4.4 m

$\sigma_{R\phi} = 173\ \mu m$
$\sigma_z = 740\ \mu m$
(isolated leptons)


ALEPH
DALI
Run=15996
Evt=7703

Limitazioni

- Risoluzione determinata da
  - Statistica della ionizzazione primaria ∝ √N
  - Spaziatura tra i fili ∝ s/√12
  - Diffusione
  - Fluttuazioni nel percorso
  - Rumore elettronico


(N. Filatova et al., NIM 143 (1977) 17)

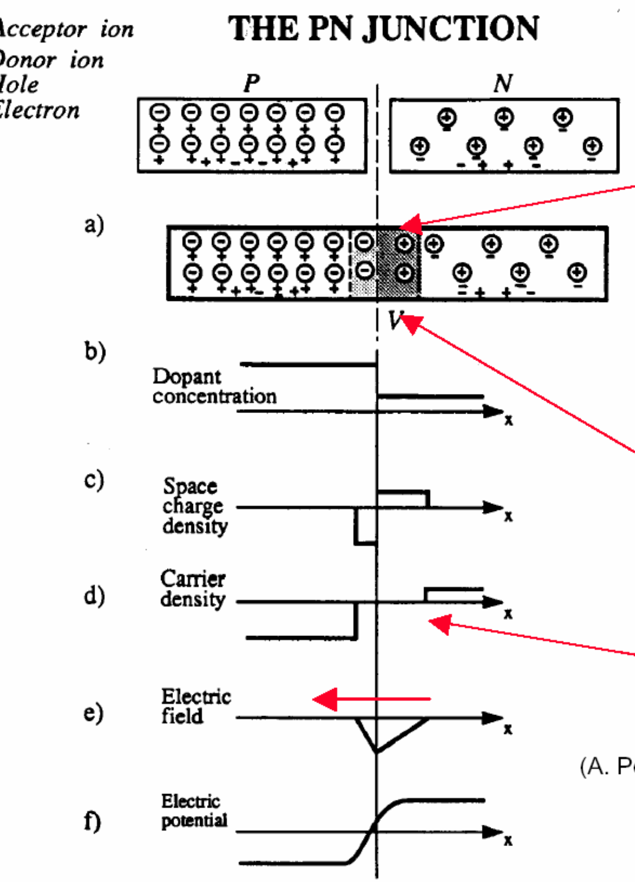
Per una maggiore precisione occorrono rivelatori a passo piu' piccolo

E` possibile sia con rivelatori a gas (MSGC, GEM ecc), (Lezioni di G. Spandre), ma meglio con i rivelatori al silicio (Lezioni di R. Dell'Orso)

Rivelatori al silicio

- Band gap: E_g =1.12 V.
- E(e^--hole pair) = 3.6 eV, (≈ 30 eV for gas detectors).
- High specific density (2.33 g/cm^3) → ΔE/track length for M.I.P.'s.: 390 eV/μm ≈ 108 e-h/ μm (average)
- High mobility: μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs
- Detector production by microelectronic techniques → small dimensions → fast charge collection (<10 ns).
- Rigidity of silicon allows thin self supporting structures. Typical thickness 300 μm → ≈ 3.2 ·10^4 e-h (average)
- But: No charge multiplication mechanism!

- Tempo di collezione di carica, diffusione
  - Velocita` di deriva dei portatori di carica v=μE, drift time, t_d = d/v = d/μE
  - Valori tipici: d=300 μm, E= 2.5kV/cm, μ_e= 1350 cm^2 / V·s, μ_h= 450 cm^2 / V·s,
  - **t_d(e)= 9ns , t_d(h)= 27ns**

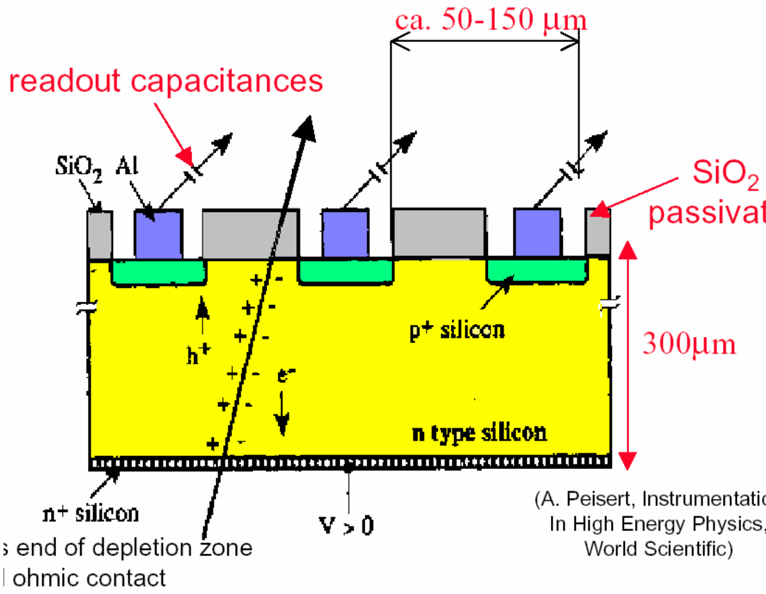


diffusion of e⁻ into p-zone, h⁺ into n-zone → potential difference stopping diffusion

thin depletion zone

no free charge carriers in depletion zone

(A. Peisert, Instrumentation In High Energy Physics, World Scientific)



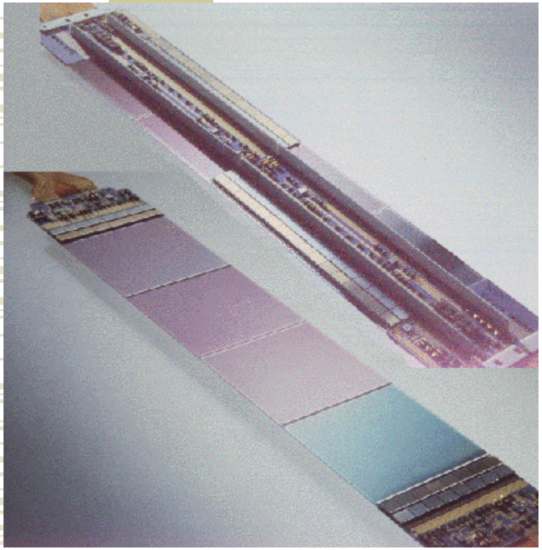
(A. Peisert, Instrumentatio In High Energy Physics, World Scientific)

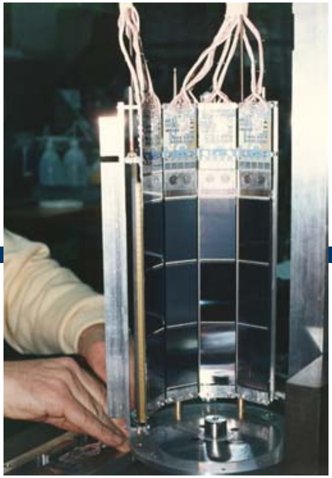
$dE/dx)_{Si}$ = 3.88 MeV/cm, per 300µm spessore ⇒ 116 keV

Questa e' l'energia media, la perdita piu' probabile e' data dal picco della Landau: (0.7× media) ⇒ 81 keV

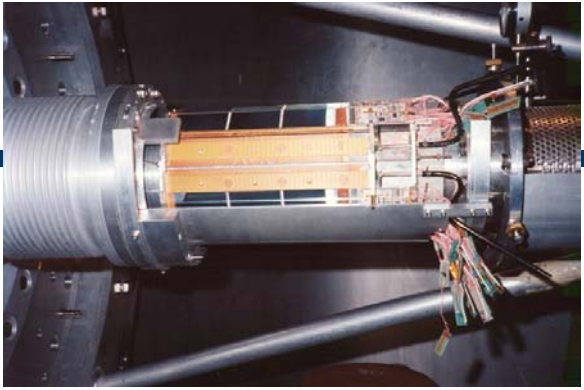
3.6eV per formare una coppia elettrone lacuna:

Carica collezionata ⇒ 22500 e (=3.6fC)

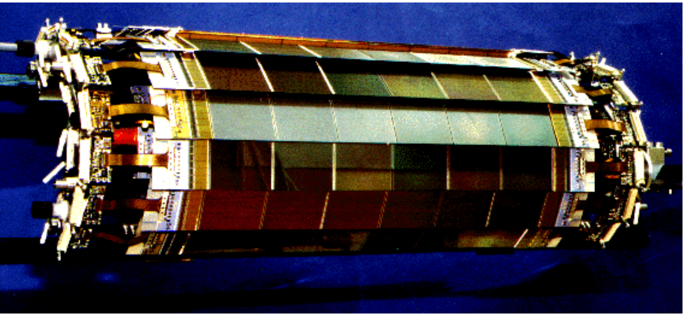


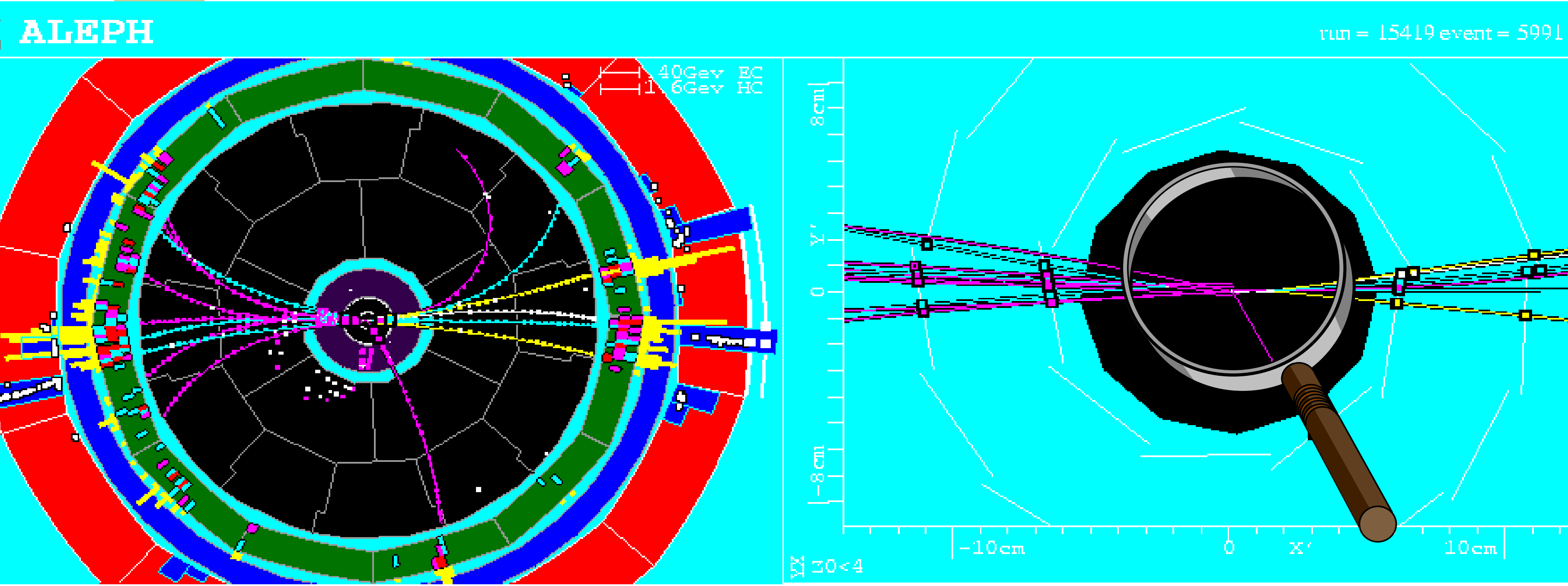


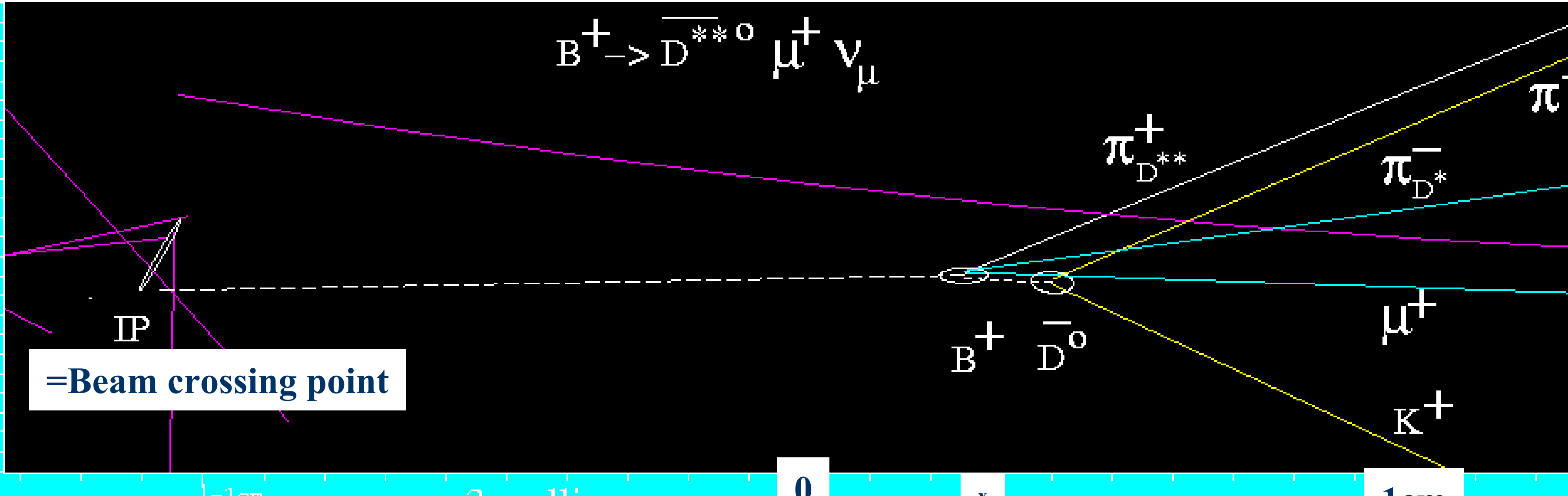
OPAL VDET



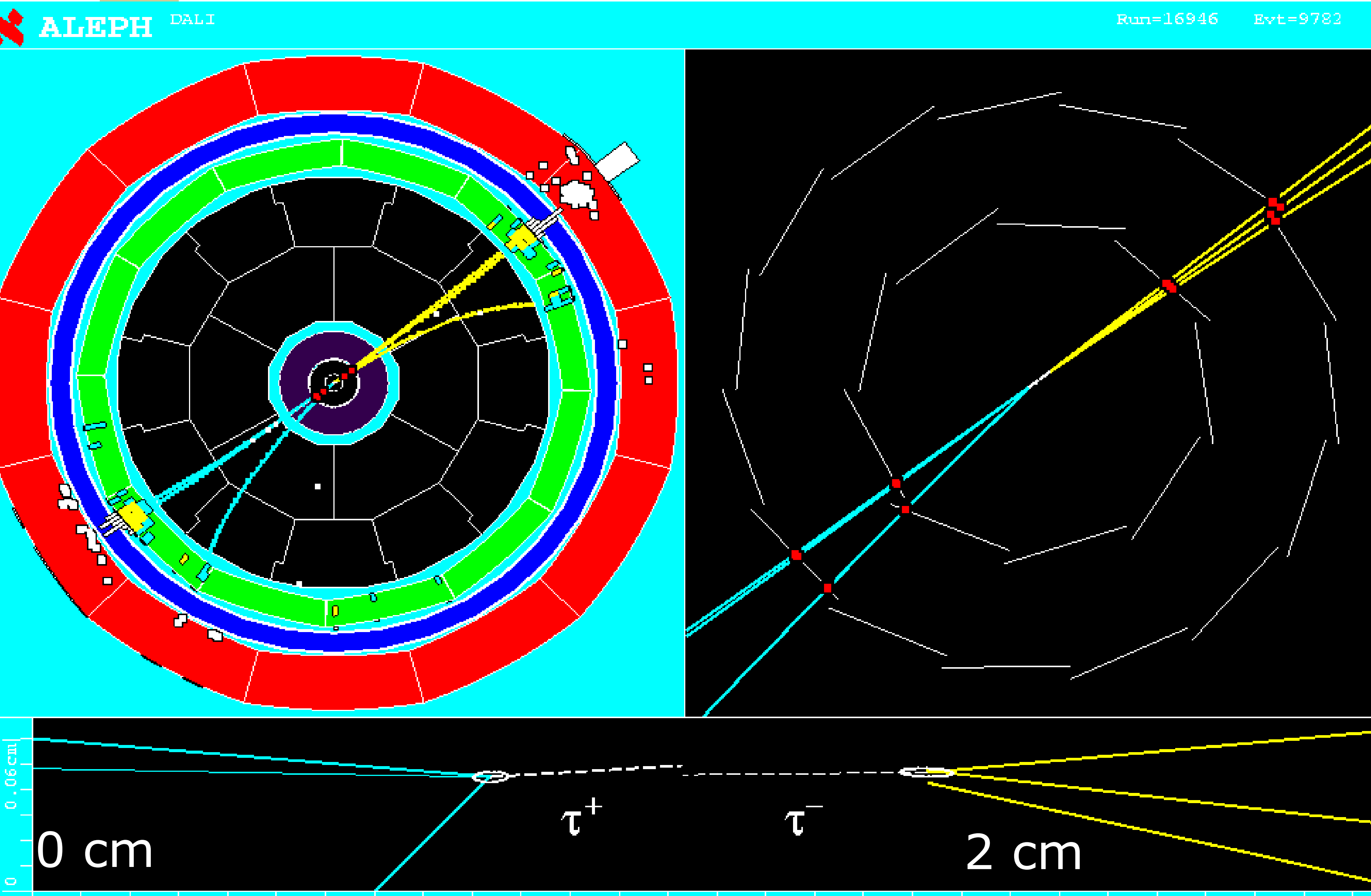
ALEPH VDET





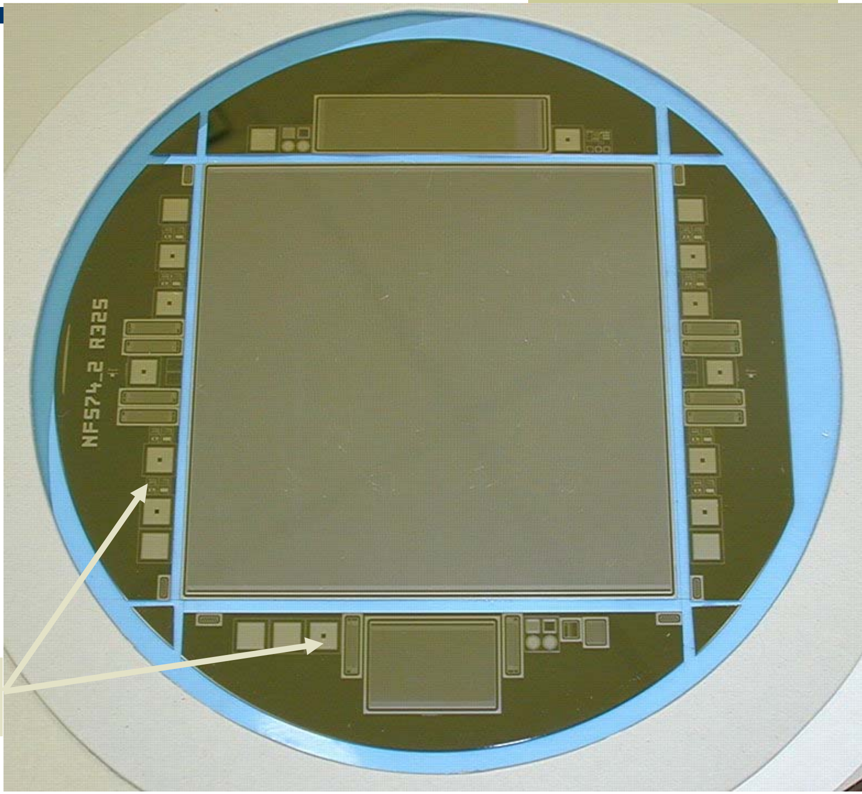


=Beam crossing point

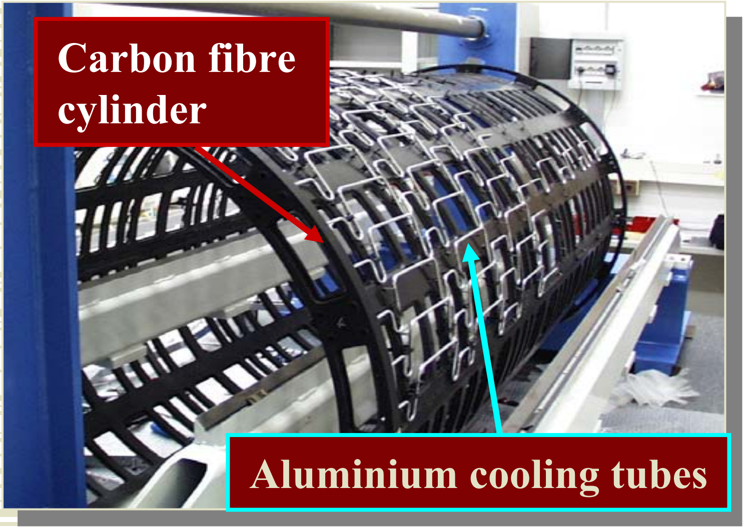


Vita media del tau $\tau = 290 \times 10^{-15}$ sec !! --> $c\tau = 87\ \mu m$

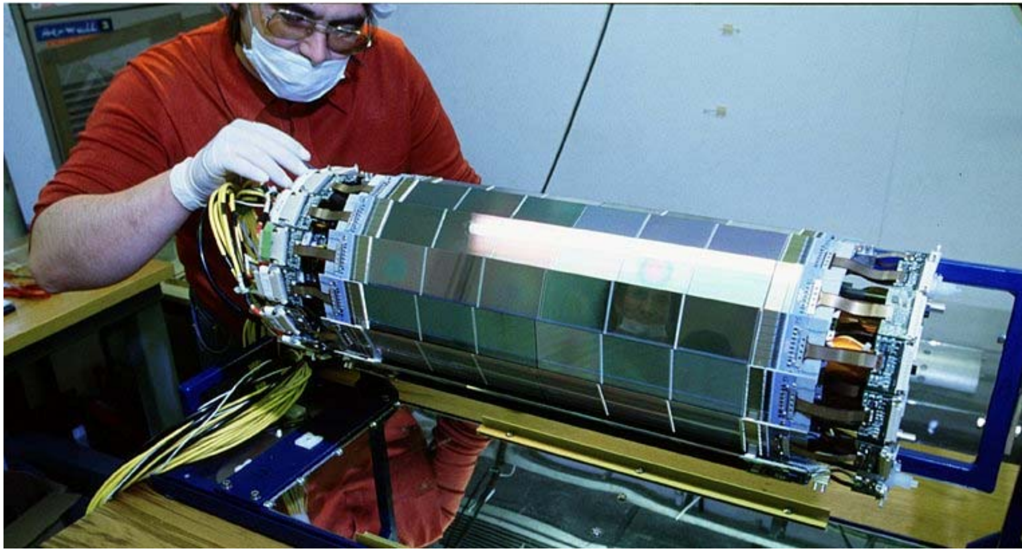
CMS silicon strip sensor from 6” wafer



Test structures



CMS prototype structure



ALEPH 1998

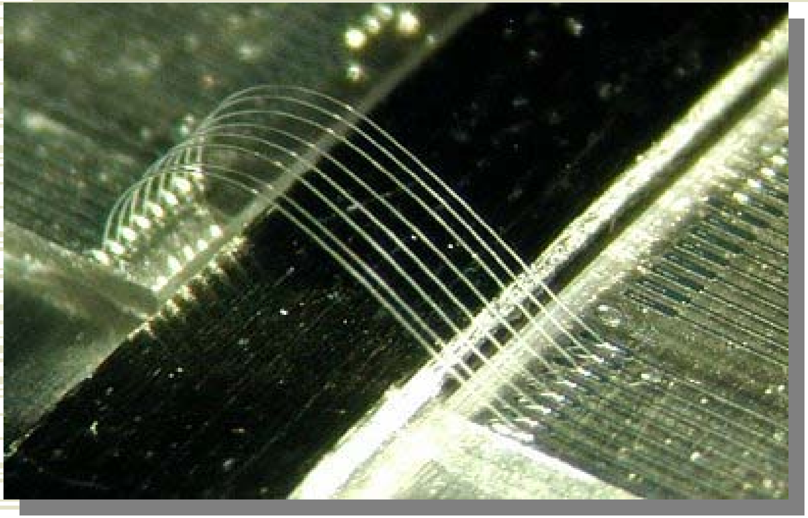
OPAL (LEP) module

~200 wire bonds

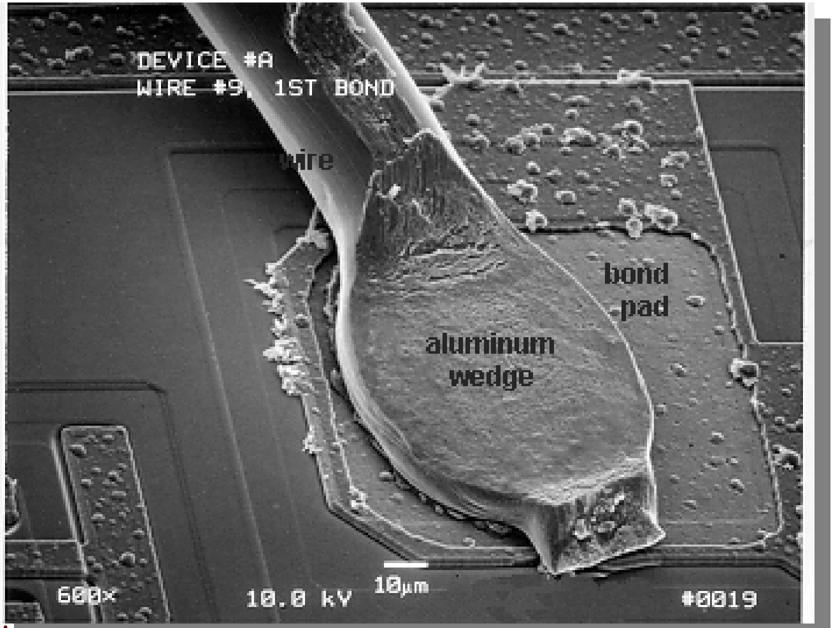
4 x 640 wire bonds

Total ~2700 wire bonds

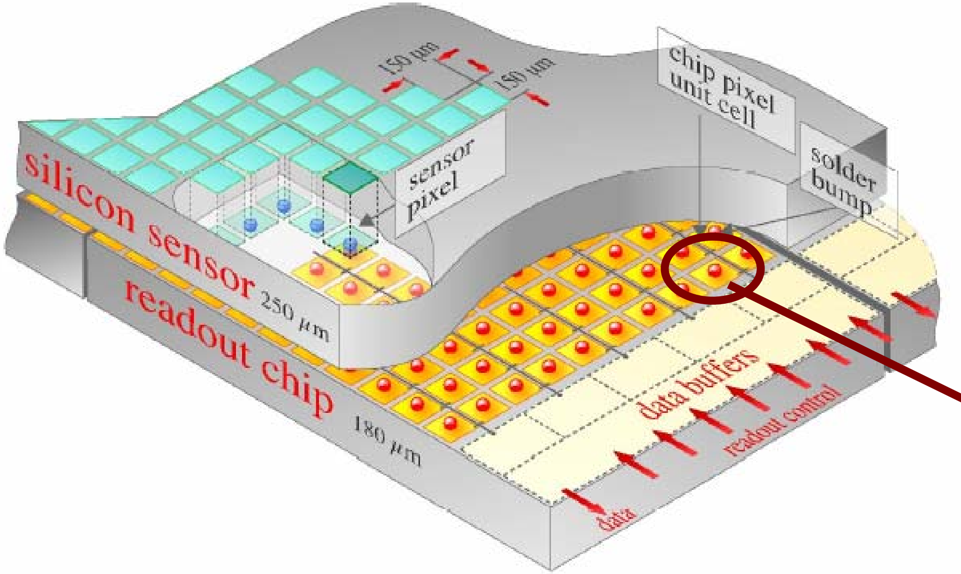
Vista al microscopio delle connessioni dei fili tra il sensore e l’elettronica di uscita

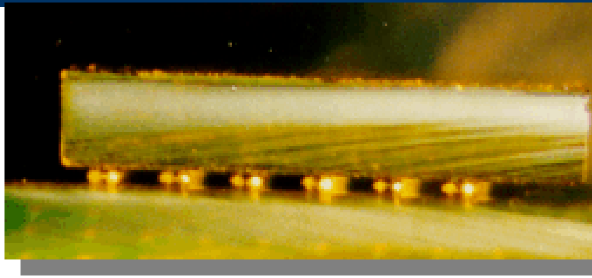


Electron micrograph of bond “foot”

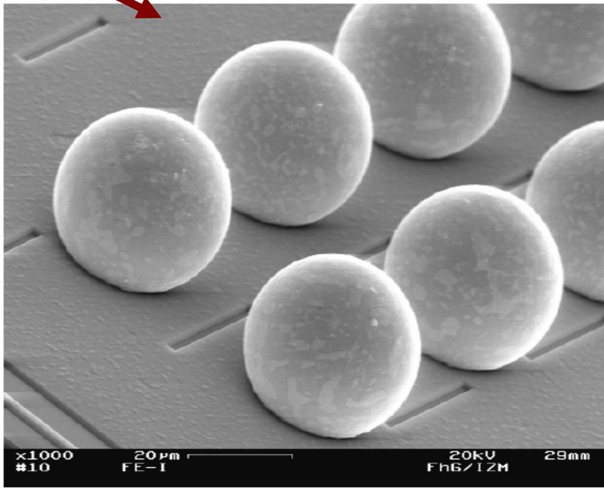


Pixel detectors



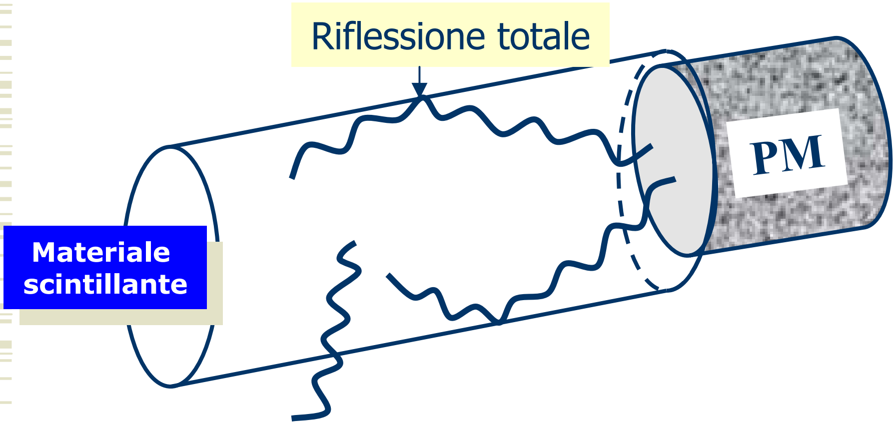


- Risoluzioni ~ 15 µm
- Punti 3-dimensionali
- Possibile equipaggiare grandi aree (~ 1m^2)
- Veloci
- Resistenti alla radiazione
- Verranno utilizzati a LHC

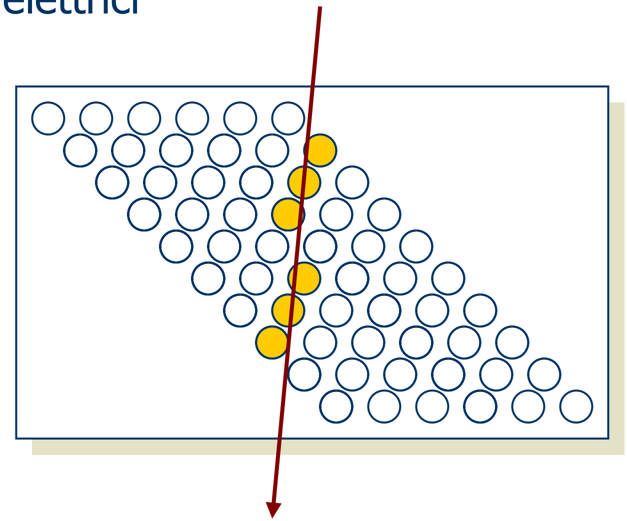


Fibre scintillanti

- Certi materiali emettono luce al passaggio di una particella carica (scintillatori plastici, polimeri aromatici ...)
- Possono essere estremamente veloci! (pochi ns)



fotomoltiplicatore: conversione della luce in segnali elettrici



Molte fibre vicine

→Rivelazione della traccia

risoluzione : pochi 100 μm/punto,
giu’ a < 50μm nel futuro

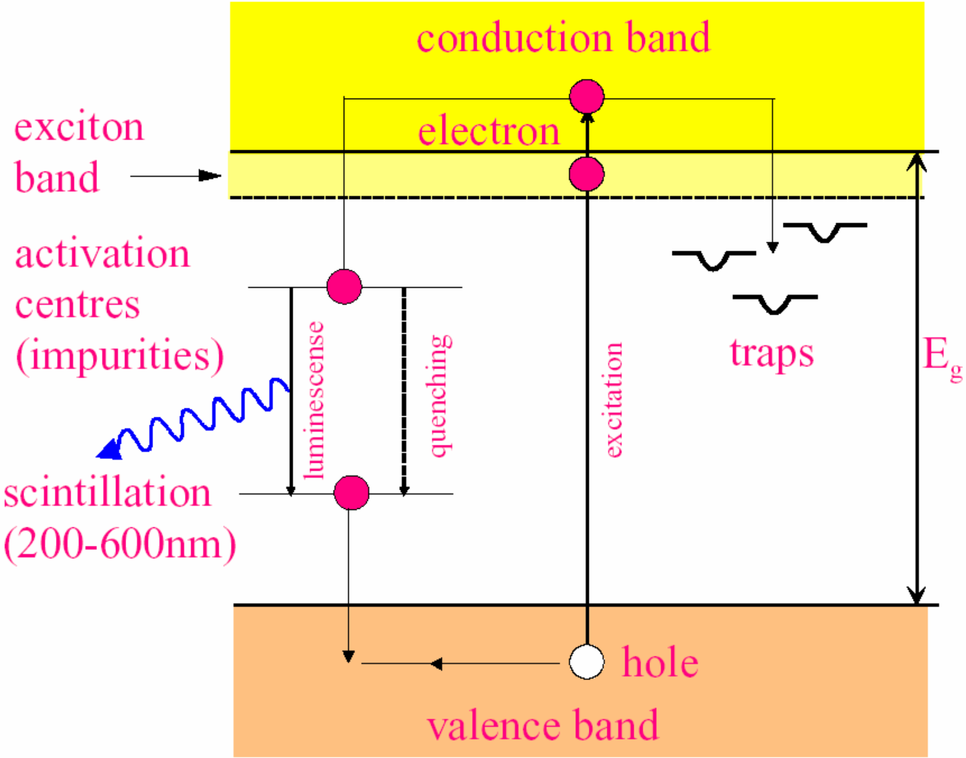
Fibre scintillanti

Usate per

- Timing
- Calorimetria
- tracciatura

1a. Inorganic crystalline scintillators (NaI, CsI, BaF_2...)

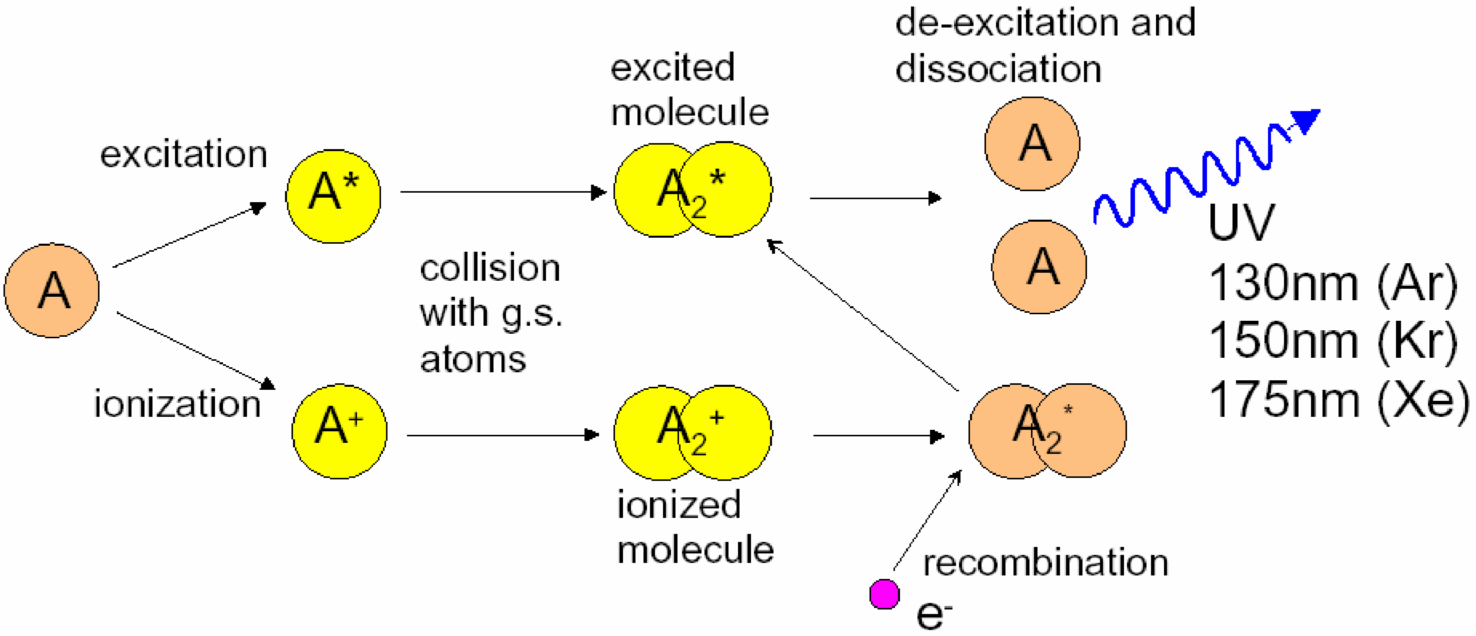
Le particelle ionizzanti attraversando il materiale creano coppie elettrone-lacuna nella banda di eccitazione.
Quando questi trovano un centro attivatore (impurezza) o una trappola allora emettono
fotoni di scintillazione



often ≥ 2 time constants:
- fast recombination (ns-µs) from activation centre
- delayed recombination due to trapping (≈ 100 ms)

Due to the high density and high Z inorganic scintillator are well suited for detection of charged particles, but also of γ.

1b. Liquid noble gases (LAr, LXe, LKr)



excitation

ionization

A

A^*

A^+

collision with g.s. atoms

excited molecule

A_2^*

ionized molecule

A_2^+

de-excitation and dissociation

A

A

A_2^*

recombination

e^-

UV
130nm (Ar)
150nm (Kr)
175nm (Xe)

also here one finds 2 time constants: few ns and 100-1000 ns, but same wavelength.

Table A6.2 Properties of some inorganic scintillators

	scintillator composition	density (g/cm^3)	index of refraction	wavelength of maximum emission (nm)	decay time constant (μs)	scintillation pulse height$^{1)}$	notes	Photons/MeV
	NaI	3.67	1.78	303	0.06	190	2)	
CLEO (CESR)	NaI(Tl)	3.67	1.85	410	0.25	100	3)	4×10^4
	CsI	4.51	1.80	310	0.01	6	3)	
	CsI(Tl)	4.51	1.80	565	1.0	45	3)	1.1×10^4
	CaI(Na)	4.51	1.84	420	0.63	85	3)	
	KI(Tl)	3.13	1.71	410	0.24/2.5	24	3)	
	^{6}LiI(Eu)	4.06	1.96	470-485	1.4	35	3)	1.4×10^4
	CaF_2(Eu)	3.19	1.44	435	0.9	50		
	BaF_2	4.88	1.49	190/220 310	0.0006 0.63	5 15		6.5×10^3 2×10^3
L3 (LEP)	$Bi_4Ge_3O_{12}$	7.13	2.15	480	0.30	10		2.8×10^3
	$CaWO_4$	6.12	1.92	430	0.5/20	50		
	$ZnWO_4$	7.87	2.2	480	5.0	26		
	$CdWO_4$	7.90	2.3	540	5.0	40		
	CsF	4.65	1.48	390	0.005	5	3)	
	CeF_3	6.16	1.68	300 340	0.005 0.020	5		
	ZnS(Ag)	4.09	2.35	450	0.2	150	4)	
	GSO	6.71	1.9	440	0.060	20		
	ZnO(Ga)	5.61	2.02	385	0.0004	40	4)	
	YSO	4.45	1.8	420	0.035	50		
	YAP	5.50	1.9	370	0.030	40		

$^{1)}$ relative to NaI(Tl) $^{2)}$ at 80 K $^{3)}$ hygroscopic $^{4)}$polycrystalline

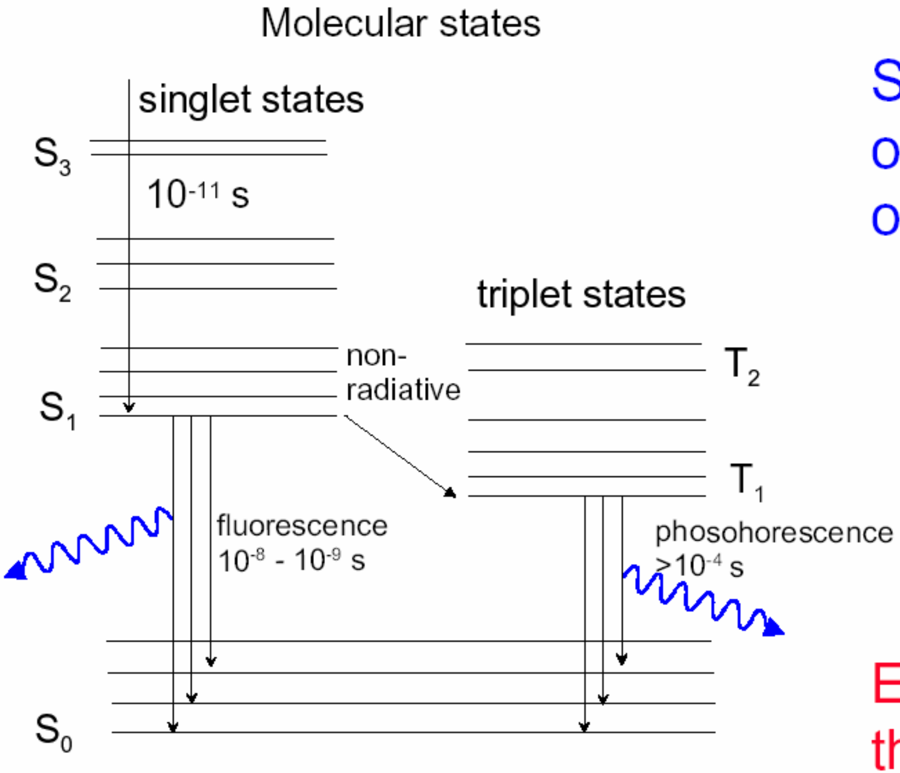
CMS (CERN)	$PbWO_4$	8.28	1.82	440, 530	0.01			100

	LAr	1.4	1.29$^{5)}$	120-170	0.005 / 0.860			
NA48 (CERN)	LKr	2.41	1.40$^{5)}$	120-170	0.002 / 0.085			
	LXe	3.06	1.60$^{5)}$	120-170	0.003 / 0.022			4×10^4

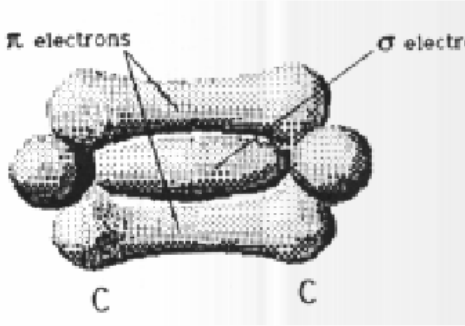
$^{5)}$ at 170 nm

Nel caso di scintillatori organici i livelli interessati sono quelli molecolari

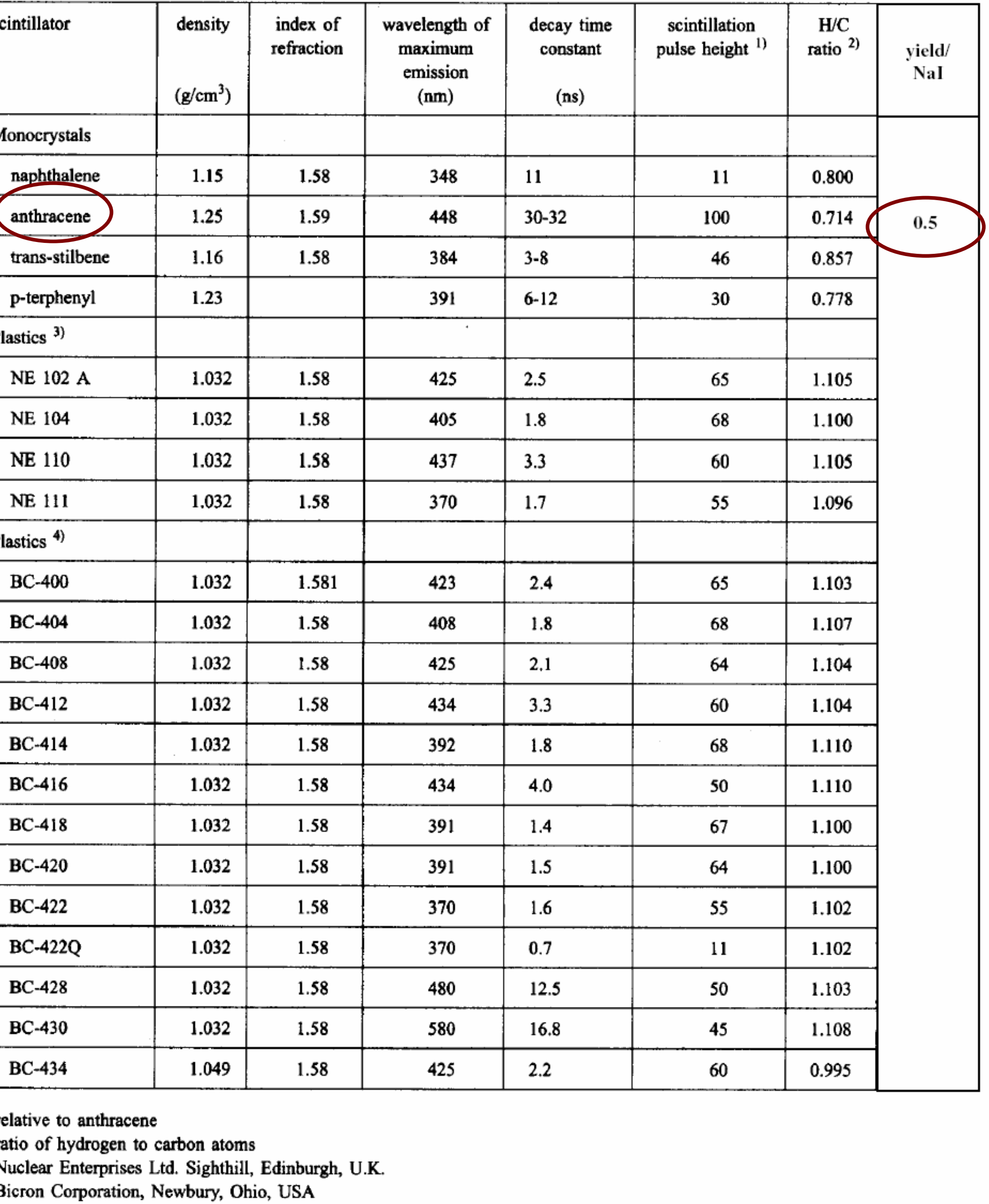
2. Organic scintillators: Monocrystals or liquids or plastic solutions



Scintillation is based on the 2 π electrons of the C-C bonds.



Emitted light is in the UV range.



cintillator	density (g/cm³)	index of refraction	wavelength of maximum emission (nm)	decay time constant (ns)	scintillation pulse height 1)	H/C ratio 2)	yield/ NaI
Monocrystals							
naphthalene	1.15	1.58	348	11	11	0.800	
anthracene	1.25	1.59	448	30-32	100	0.714	0.5
trans-stilbene	1.16	1.58	384	3-8	46	0.857	
p-terphenyl	1.23		391	6-12	30	0.778	
lastics 3)							
NE 102 A	1.032	1.58	425	2.5	65	1.105	
NE 104	1.032	1.58	405	1.8	68	1.100	
NE 110	1.032	1.58	437	3.3	60	1.105	
NE 111	1.032	1.58	370	1.7	55	1.096	
lastics 4)							
BC-400	1.032	1.581	423	2.4	65	1.103	
BC-404	1.032	1.58	408	1.8	68	1.107	
BC-408	1.032	1.58	425	2.1	64	1.104	
BC-412	1.032	1.58	434	3.3	60	1.104	
BC-414	1.032	1.58	392	1.8	68	1.110	
BC-416	1.032	1.58	434	4.0	50	1.110	
BC-418	1.032	1.58	391	1.4	67	1.100	
BC-420	1.032	1.58	391	1.5	64	1.100	
BC-422	1.032	1.58	370	1.6	55	1.102	
BC-422Q	1.032	1.58	370	0.7	11	1.102	
BC-428	1.032	1.58	480	12.5	50	1.103	
BC-430	1.032	1.58	580	16.8	45	1.108	
BC-434	1.049	1.58	425	2.2	60	0.995	

elative to anthracene
atio of hydrogen to carbon atoms
Nuclear Enterprises Ltd. Sighthill, Edinburgh, U.K.
Bicron Corporation, Newbury, Ohio, USA

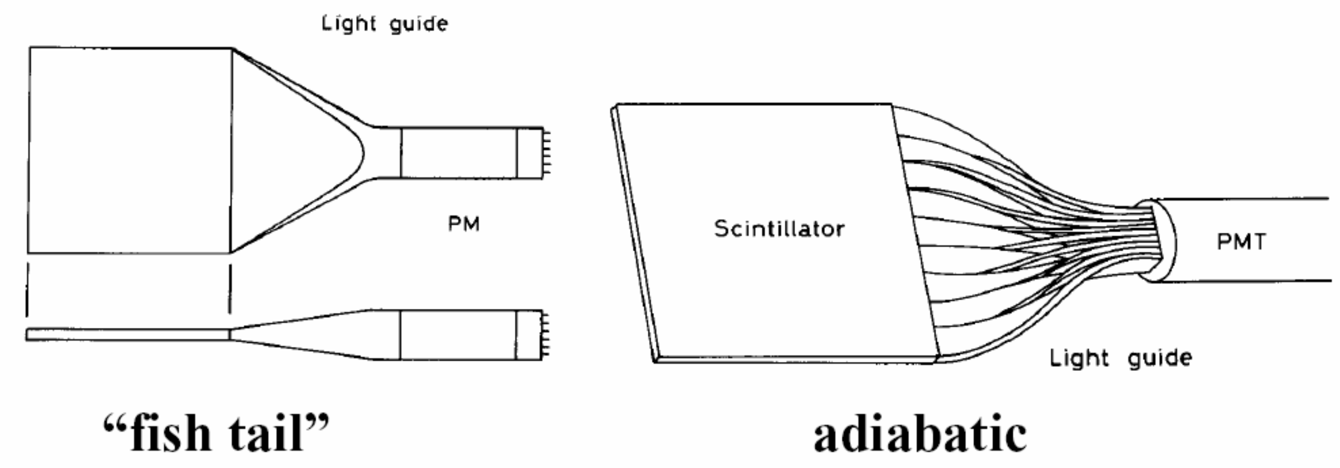
- Scintillatori organici hanno basso Z (H,C).

- Bassa efficienza di rivelazione per fotoni (praticamente solo effetto Compton).

- Alta efficienza per neutroni grazie a reazione (n,p).

Metodi di lettura

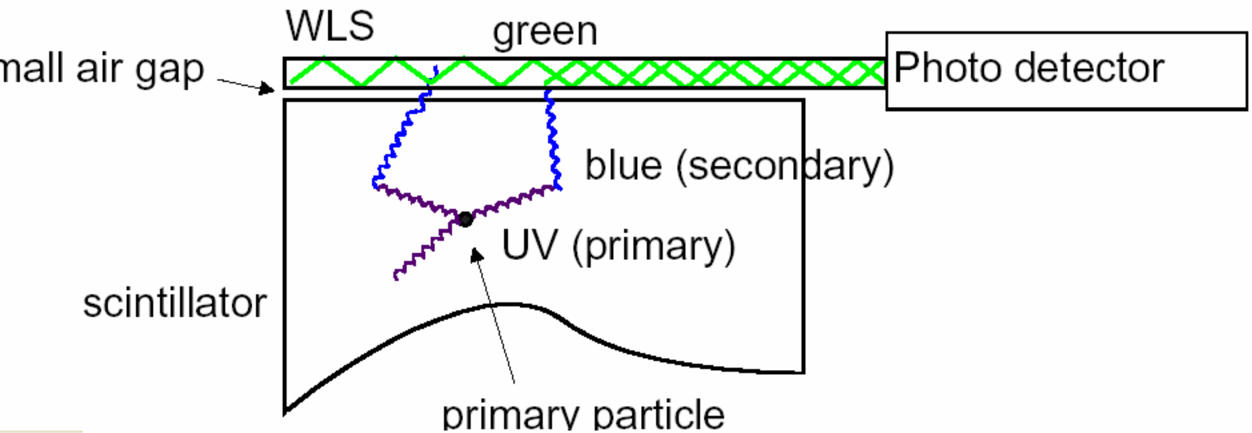
- Guide di luce :
  - riflessione interna totale



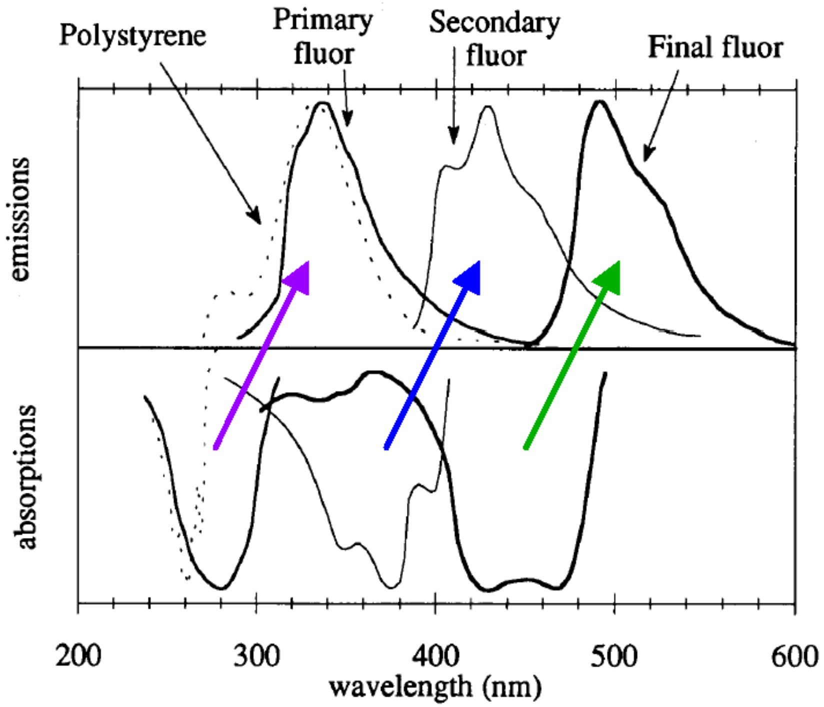
“fish tail”

adiabatic

Wavelength shifter (WLS) bars



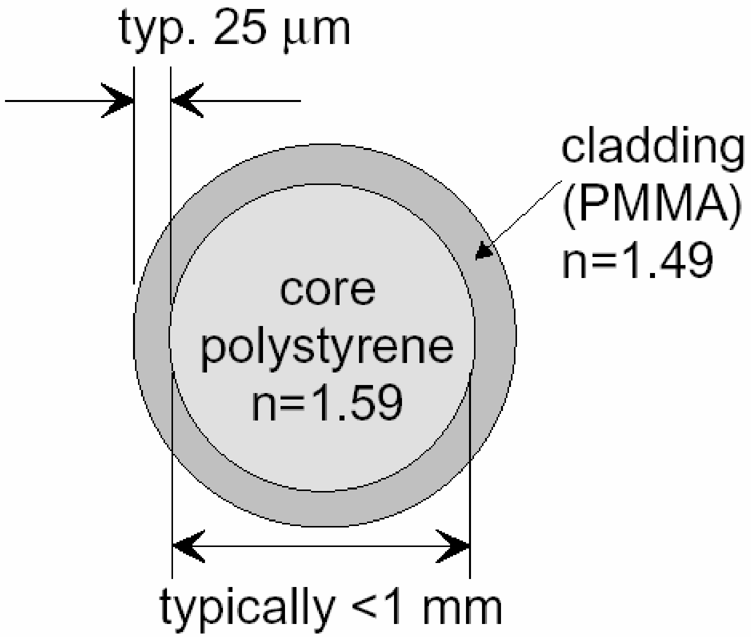
Schematic representation of wave length shifting principle

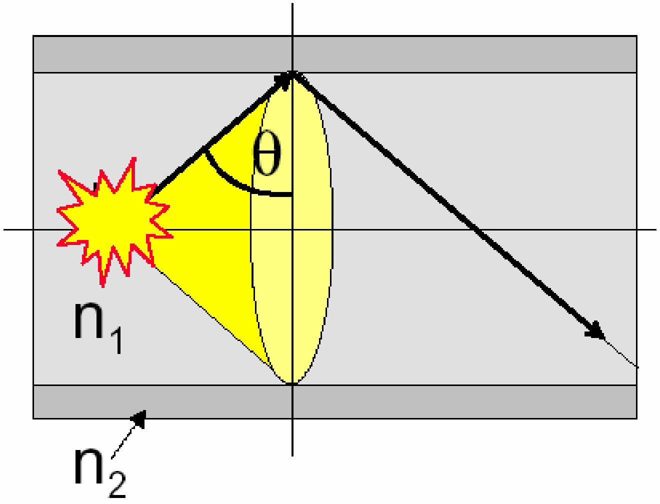


(C. Zorn, Instrumentation In High Energy Physics, World Scientific,1992)

- Optical fibers

light transport by total internal reflection





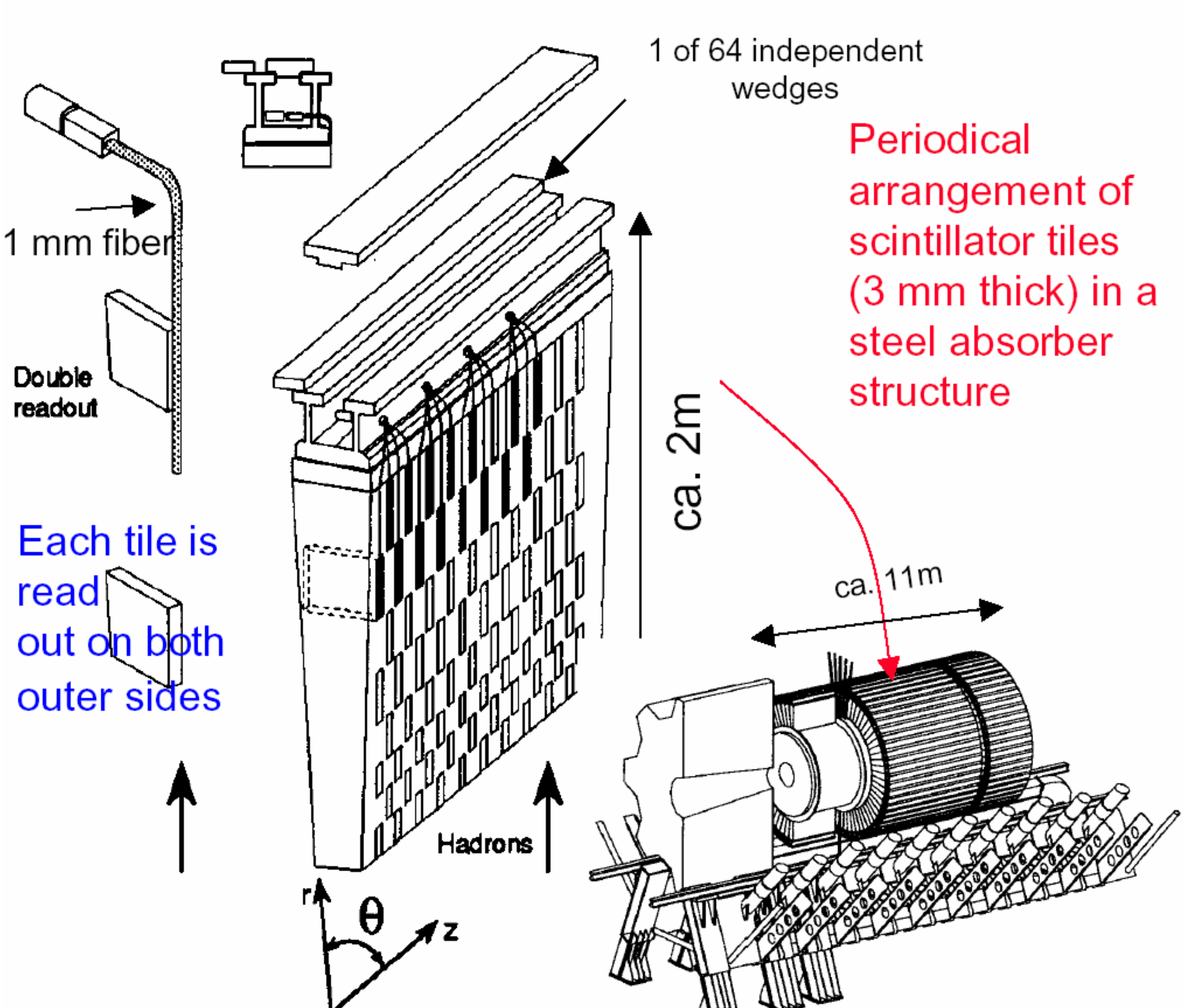
$$\theta \geq \arcsin\frac{n_2}{n_1} \approx 69.6^\circ$$

$$\frac{d\Omega}{4\pi} = 3.1\%$$ in one direction

minimize n_{cladding}.

Ideal: air (n=1), but impossible due to surface imperfections

Calorimetro adronico di ATLAS



1 of 64 independent wedges

Periodical arrangement of scintillator tiles (3 mm thick) in a steel absorber structure

Each tile is read out on both outer sides readout of a scintillator with a fiber (schematically)

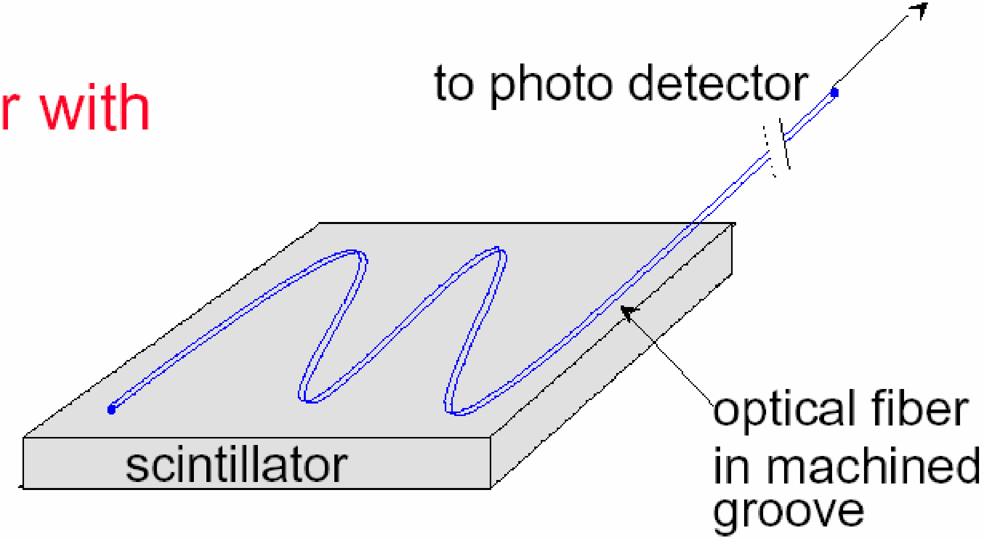
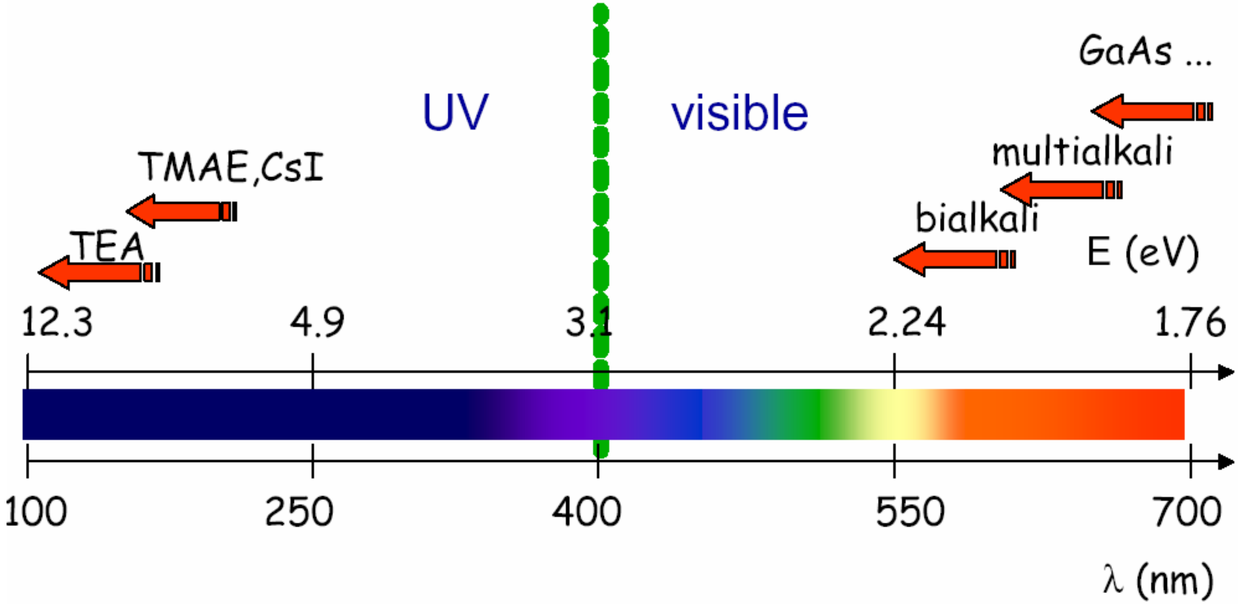


Photo Detectors

Purpose: Convert light into detectable electronics signal

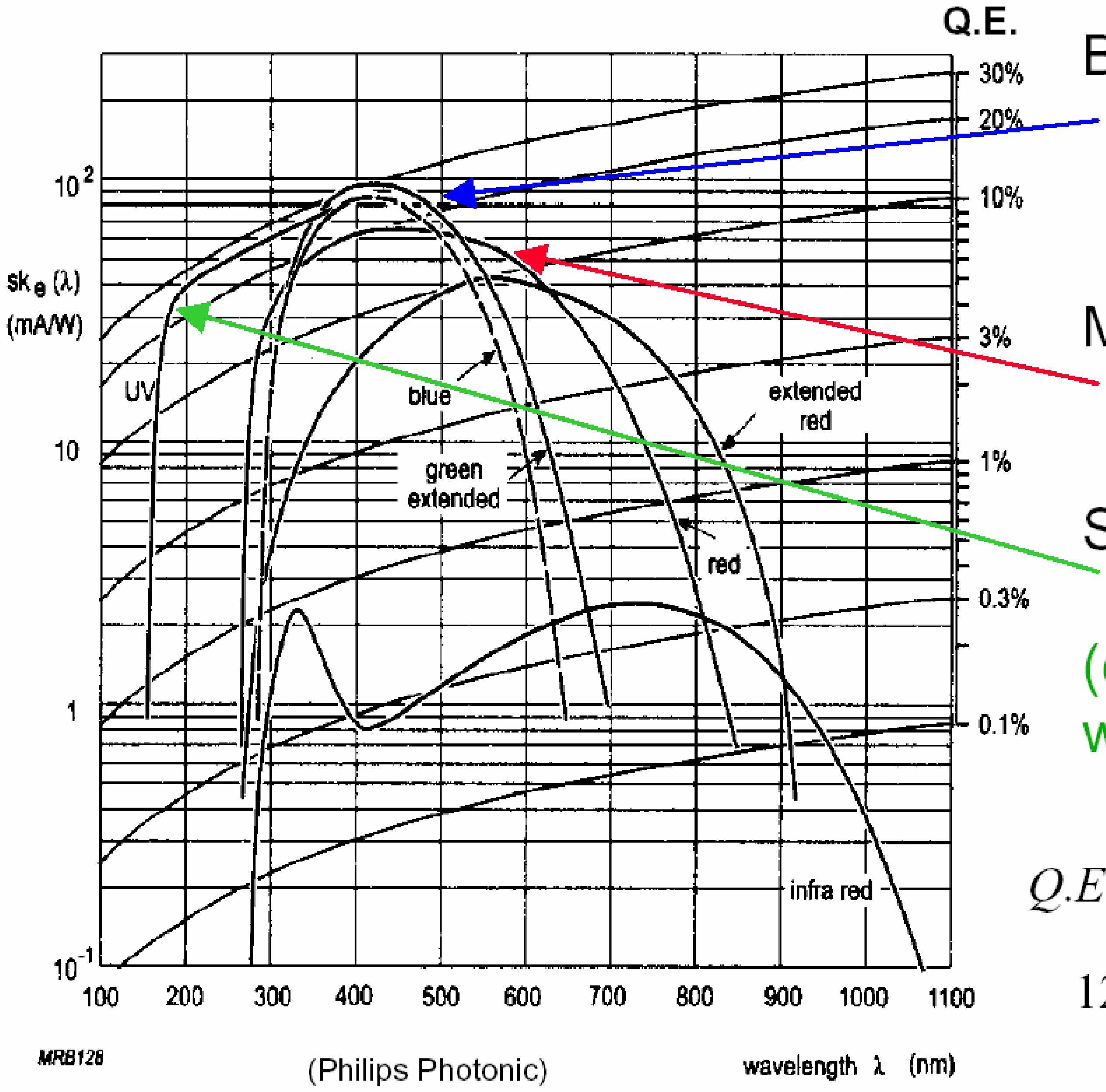
Principle: Use Photoelectric Effect to convert photons to photoelectrons

Threshold of some photosensitive material



standard requirement

- high sensitivity, usually expressed as quantum efficiency $Q.E. = N_{p.e.} / N_{photons}$



(Philips Photonic)

Bialkali

SbK_2Cs

SbRbCs

Multialkali

$SbNa_2KCs$

Solar blind

CsTe

(cut by quartz window)

$$Q.E.(\%) \approx 124 \cdot \frac{sk_e(mA/W)}{\lambda(nm)}$$

Transmission of various PM windows

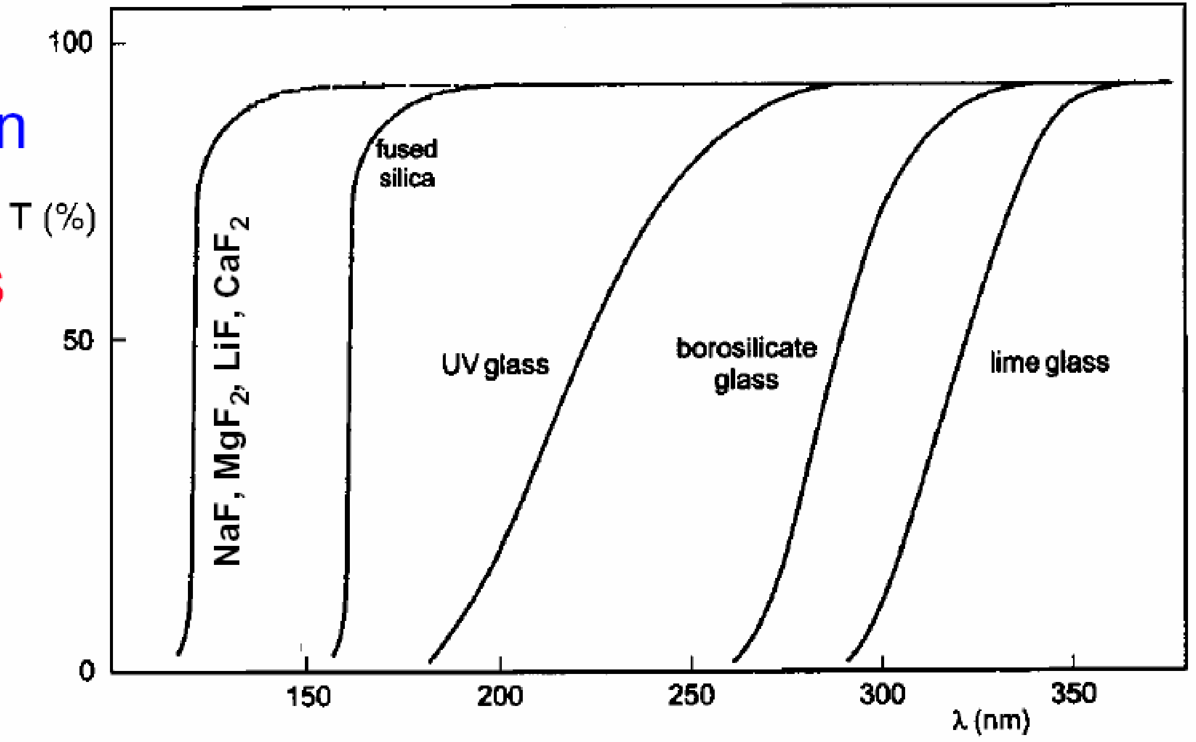
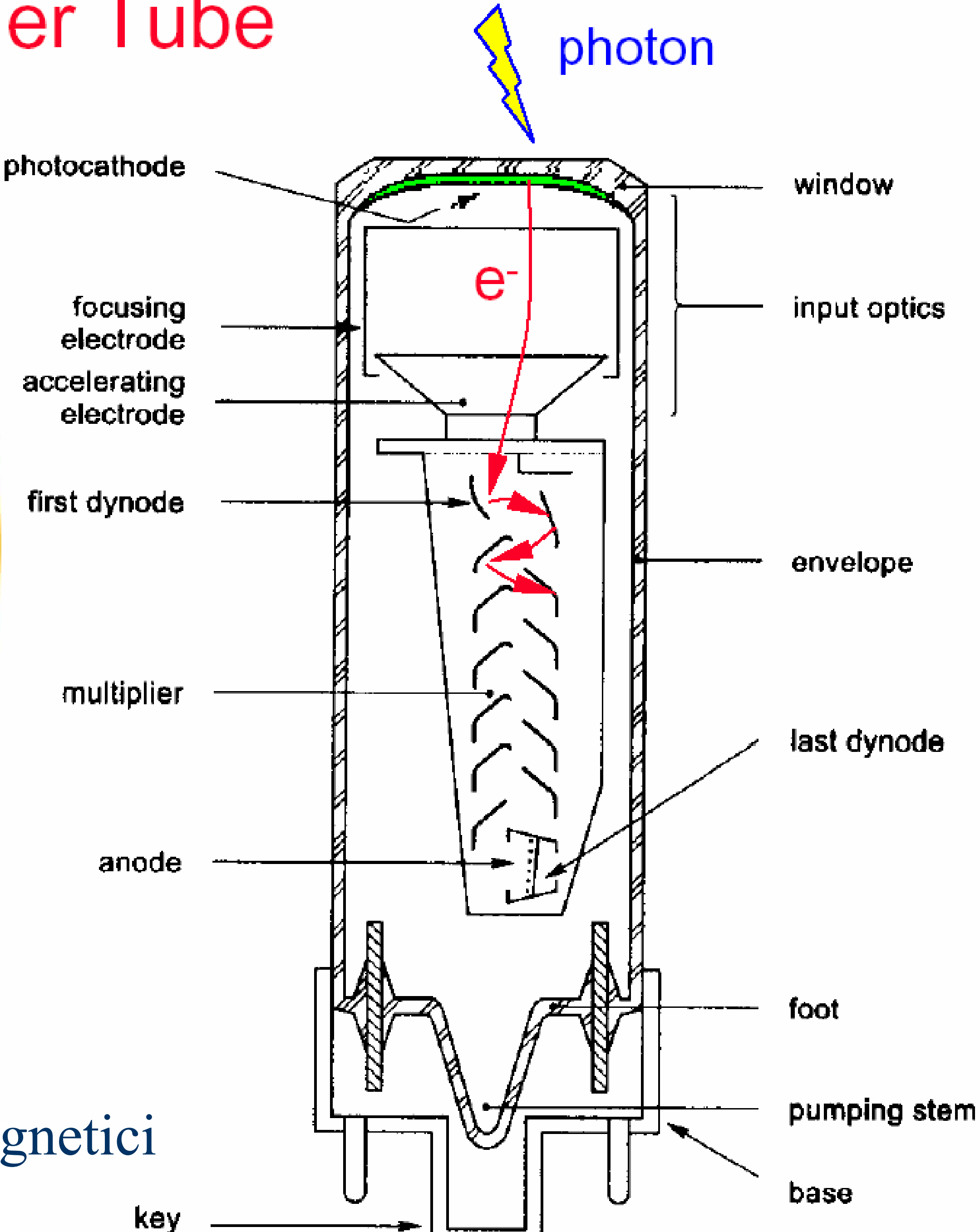


Photo Multiplier Tube (PMT)

(Philips Photonic)



Guadagni ~ 10^6

Sensibili a campi magnetici

Mu-shield

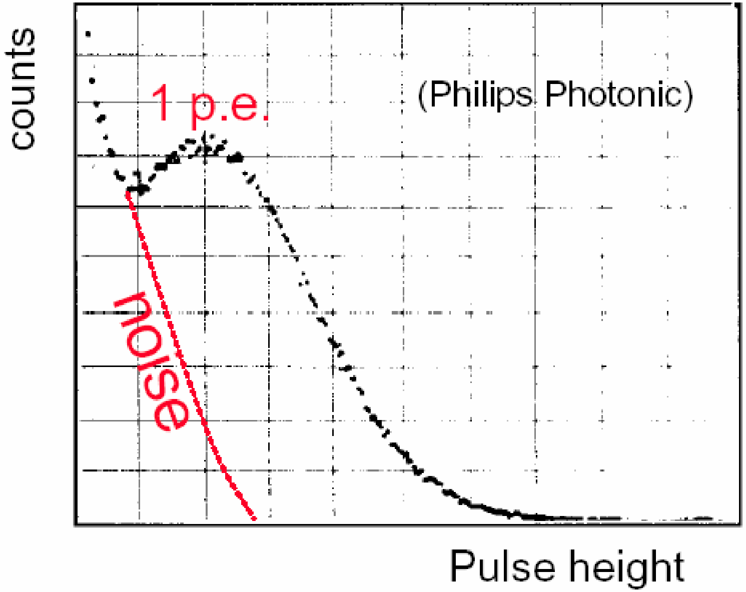
RISOLUZIONE ENERGETICA dei PMT

determinata principalmente dalle fluttazioni del numero di elettroni secondari dai dinodi

Poisson distribution: $P(\bar{n},m)=\dfrac{\bar{n}^{m}e^{-m}}{m!}$

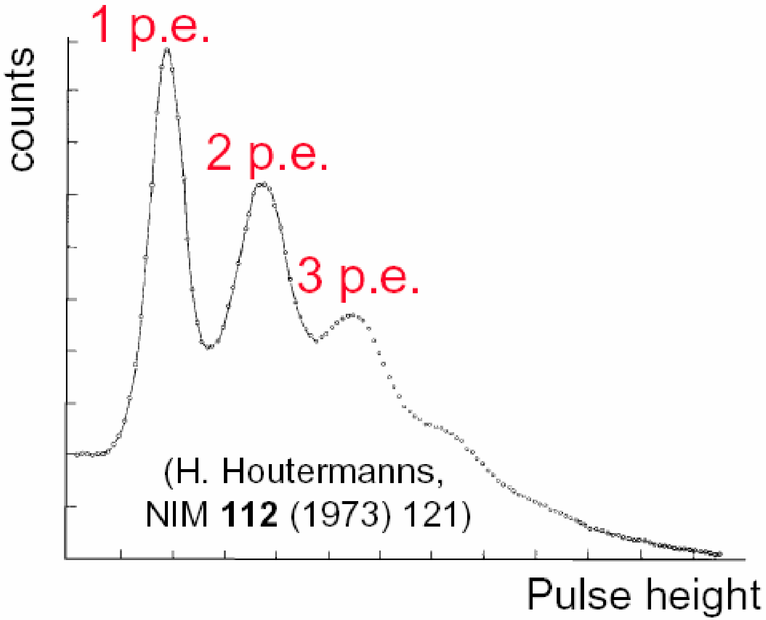
Relative fluctuation: $\dfrac{\sigma_n}{\bar{n}}=\dfrac{\sqrt{\bar{n}}}{\bar{n}}=\dfrac{1}{\sqrt{\bar{n}}}$

Single photons.
Pulse height spectrum of a PMT with Cu-Be dynodes.



(Philips Photonic)

Pulse height spectrum of a PMT with NEA dynodes.



(H. Houtermanns, NIM **112** (1973) 121)

Hybrid photo diodes (HPD)

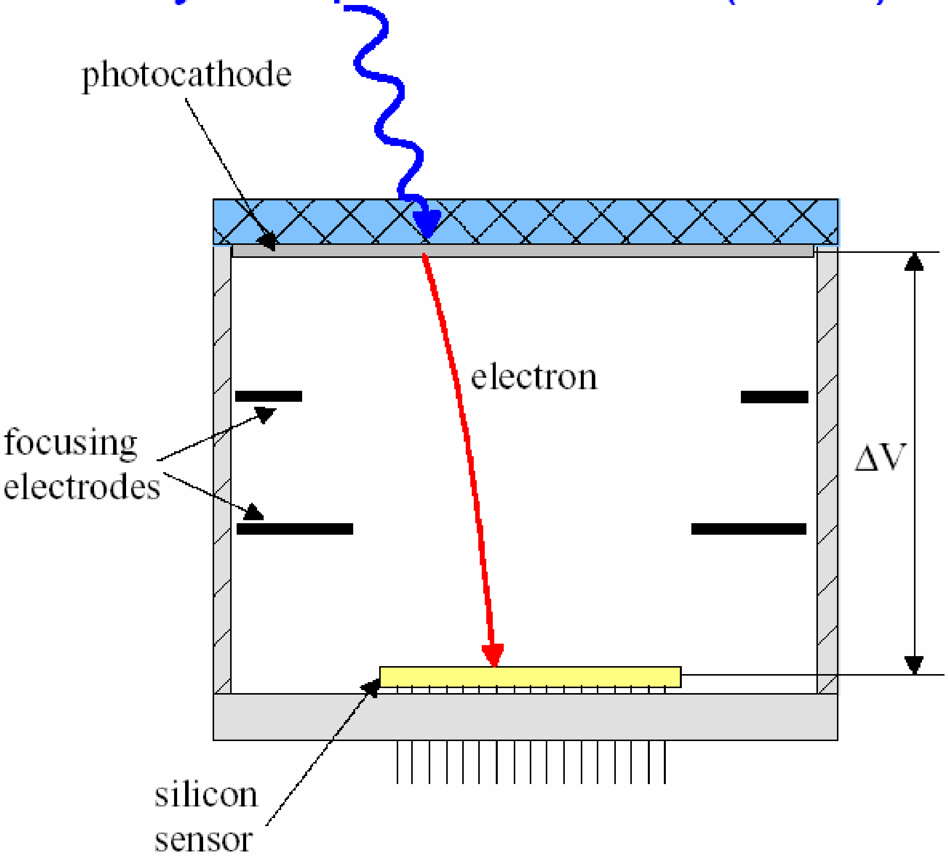


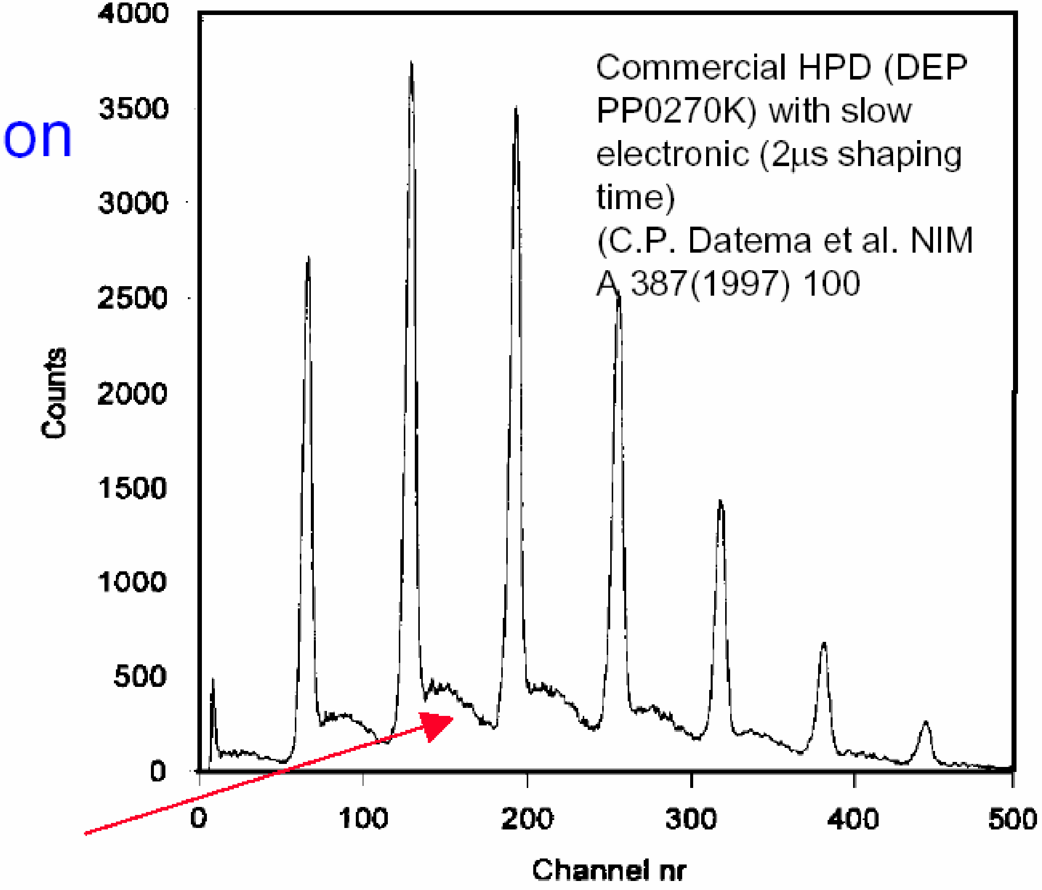
photo cathode + p.e. acceleration + silicon det. (pixel, strip, pads)

Photo cathode like in PMT, ΔV 10-20 kV

$$G = \frac{e\Delta V}{W_{Si}} = \frac{20\ keV}{3.6\ eV} \approx 5 \cdot 10^3$$ (for ΔV =20 kV)

Single photon detection with high resolution

Poisson statistics with $\bar{n}$ =5000 !



Commercial HPD (DEP PP0270K) with slow electronic (2µs shaping time)
(C.P. Datema et al. NIM A 387(1997) 100

Background from electron backscattering from silicon surface