Scintilacijski detektorji

I) Scintilatorji

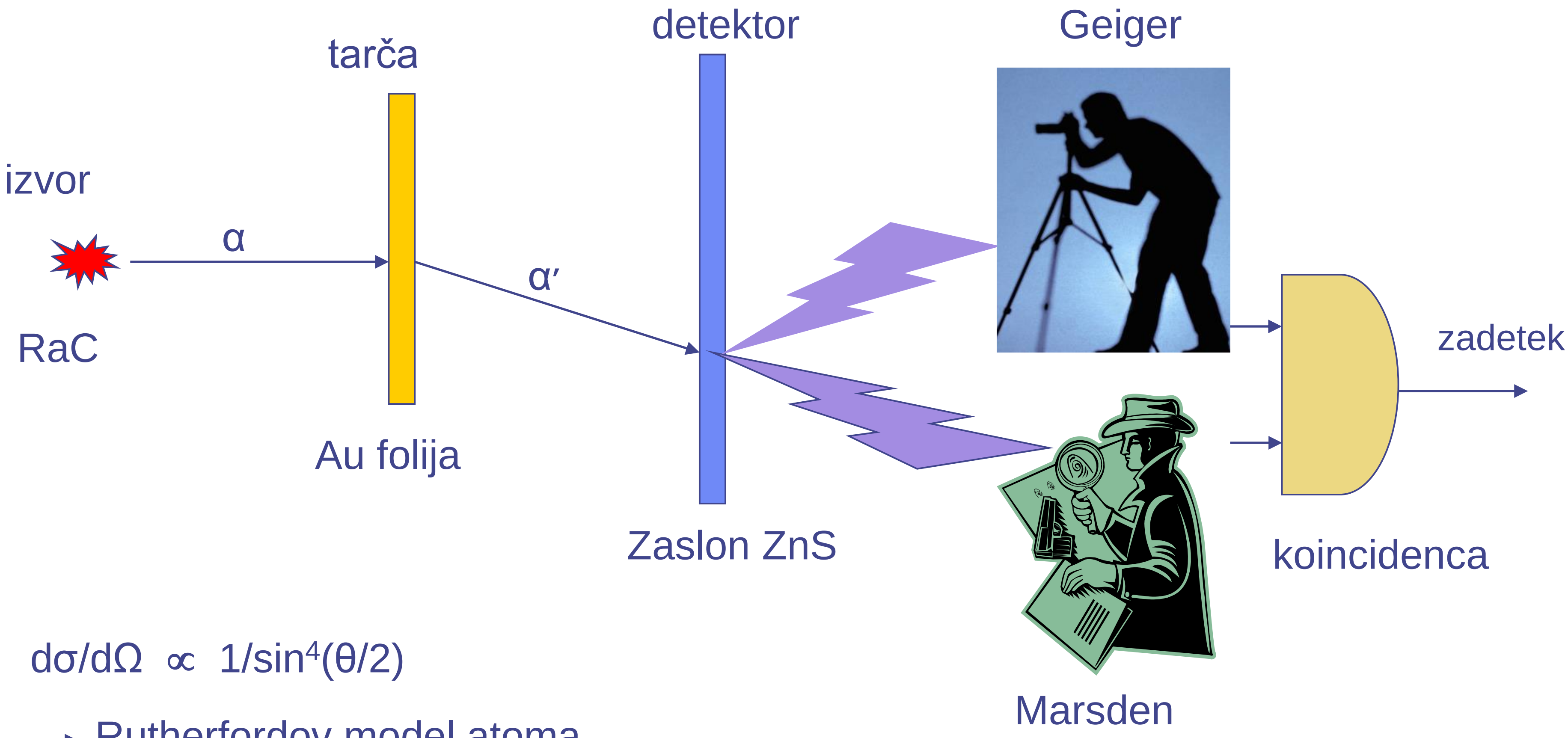
II) Detekcija svetlobe

III) Uporaba scintilacijskih detektorjev

Literatura:
G.F.Knoll: Radiation detection and measurement, John Wiley
W.R.Leo: Techniques for nuclear and particle physics experiments,
Springer-Verlag

Zgodovina I

1911 Rutherfordov eksperiment – prvi scintilacijski števec

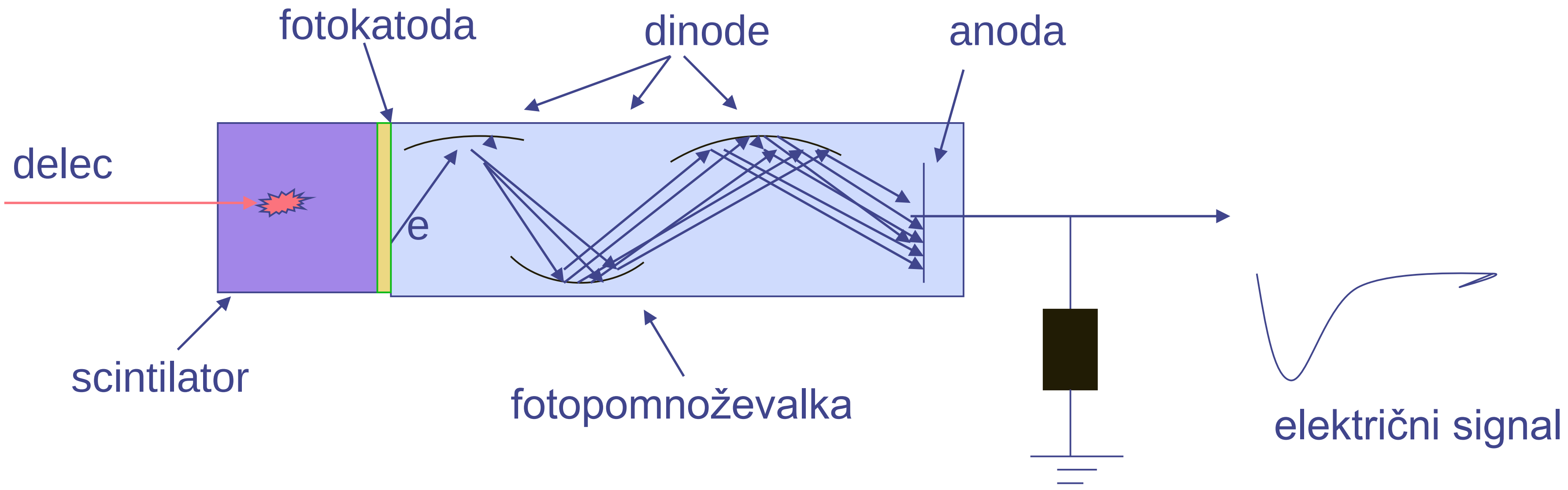


$d\sigma/d\Omega \propto 1/\sin^4(\theta/2)$

→ Rutherfordov model atoma

Zgodovina II

- 1944 Curran in Baker - fotopomnoževalka



NaI(Tl) - 1948, Robert Hofstadter

I) Scintilatorji

1) mehanizem produkcije svetlobe
   in vrste scintilatorjev

   a) anorganski b) organski c) žlahtni plini
2) pridelek fotonov
3) časovni potek scintilacij
4) zbiranje svetlobe na fotopomnoževalki

Table 7.1. Physical properties of various commercial scintillators (data from Nuclear Enterprises scintillator catalog [7.1])

	Scintillator	Type	Density	Refractive index	Melting softening or boiling point C^a	Light output (% Anthracene)	Decay constant, main component [ns]	Wavelength of maximum emission [nm]	Content of loading element (% by wt.)	H/C No. of H atoms/ No. of C atoms	Principal applications
Plastic	NE 102A	Plastic	1.032	1.581	75	65	2.4	423		1.104	γ, α, β, fast n
	NE 104	Plastic	1.032	1.581	75	68	1.9	406		1.100	ultra-fast counting
	NE 104B	Plastic	1.032	1.58	75	59	3.0	406		1.107	with BBQ light guides
	NE 105	Plastic	1.037	1.58	75	46		423		1.098	dosimetry
	NE 110	Plastic	1.032	1.58	75	60	3.3	434		1.104	γ, α, β, fast n etc.
	NE 111A	Plastic	1.032	1.58	75	55	1.6	370		1.103	ultra-fast timing
	NE 114	Plastic	1.032	1.58	75	50	4.0	434		1.109	as for NE 110
	NE 160	Plastic	1.032	1.58	80	59	2.3	423		1.105	use at high temperature
	Pilot U	Plastic	1.032	1.58	75	67	1.36	391		1.100	ultra fast timing
	Pilot 425	Plastic	1.19	1.49	100			425		1.6	Cherenkov detector
Liquid	NE 213	Liquid	0.874	1.508	141	78	3.7	425		1.213	fast n (P.S.D.)
	NE 216	Liquid	0.885	1.523	141	78	3.5	425		1.171	α, β (internal counting)
	NE 220	Liquid	1.036	1.442	104	65	3.8	425	O 29%	1.669	internal counting, dosim
	NE 221	Gel	1.08	1.442	104	55	4	425		1.669	α, β (internal counting)
	NE 224	Liquid	0.877	1.505	169	80	2.6	425		1.330	γ, fast n
	NE 226	Liquid	1.61	1.38	80	20	3.3	430		0	γ, insensitive to n
	NE 228	Liquid	0.71	1.403	99	45		385		2.11	n
	NE 230	Deuterated liquid	0.945	1.50	81	60	3.0	425	D 14.2%	0.984	(D/C) special applicatio
	NE 232	Deuterated liquid	0.89	1.43	81	60	4	430	D 24.5%	1.96	(D/C) special applicatio
	NE 233	Liquid	0.874	1.506	117	74	3.7	425		1.118	α, β (internal counting)
	NE 235	Liquid	0.858	1.47	350	40	4	420		2.0	large tanks
	NE 250	Liquid	1.035	1.452	104	50	4	425	O 32%	1.760	internal counting, dosim
Loaded liquid	NE 311 & 311A	B loaded liquid	0.91	1.411	85	65	3.8	425	B 5%	1.701	n, β
	NE 313	Gd loaded liquid	0.88	1.506	136	62	4.0	425	Gd 0.5%	1.220	n
	NE 316	Sn loaded liquid	0.93	1.496	148.5	35	4.0	425	Sn 10%	1.411	γ, x-rays
	NE 323	Gd loaded liquid	0.879	1.50	161	60	3.8	425	Gd 0.5%	1.377	n
Neutron (ZnS-type) and glass	NE 422 & 426	^{6}Li-ZnS(Ag)	2.36		110	300	200	450	Li 5%		slow n
	NE 451	ZnS(Ag) plastic	1.443		110	300	200	450			fast n
	NE 901, 902, 903	Glass	2.64	1.58	c. 1200	28	20 & 60	395	Li 2.3%		n, β
	NE 904, 905, 906	Glass	2.5	1.55	c. 1200	25	20 & 58	395	Li 6.6%		n
	NE 907, 908	Glass	2.42	1.566	c. 1200	20	18 & 62	399	Li 7.5%		n
	NE 912, 913	Glass	2.3	1.55	c. 1200	25	18 & 55	397	Li 7.7%		n, β (low background)
Crystal	Anthracene	Crystal	1.25	1.62	217	100	30	447		0.715	γ, α, β, fast n
	Stilbene	Crystal	1.16	1.626	125	50	4.5	410		0.858	fast n (P.S.D.), γ, etc.
	NaI(Tl)	Crystal	3.67	1.775	650	230	230	413			γ, x-rays
	NaI(pure)	Crystal	3.67	1.775	651	440^b	60^b	303^b			γ, x-rays (fast counting)
	LiI(Eu)	Crystal	4.06	1.955	445	75	1200	475			n
	CsI(Tl)	Crystal	4.51	1.788	620	95	1100	580			heavy particles, γ (P.S.I
	CsI(Na)	Crystal	4.51	1.787	621	150.190	650	420			heavy particles, γ (P.S.I
	CsI(pure)	Crystal	4.51	1.788	621	500^b	600^b	c. 400^b			heavy particles, γ (low energy)
	CaF$_2$(Eu)	Crystal	3.17	1.443	1418	110	1000	435			β, x-rays etc.
	CaWO$_4$	Crystal	6.1	1.92	1535	36	6000	430			γ (seldom used)
	ZnS(Ag)	Multi-crystal	4.09	2.356	1850	300	200	450			α
	ZnO(Ga)	Multi-crystal	5.61	2.02	1975	90	1.48	385			α

[a] Although NE 160 begins to soften very slightly at approximatley 80 °C, it retains its shape up to at least 150 °C unlike other plastic scintillators as NE 102A

[b] At liquid nitrogen temperature.

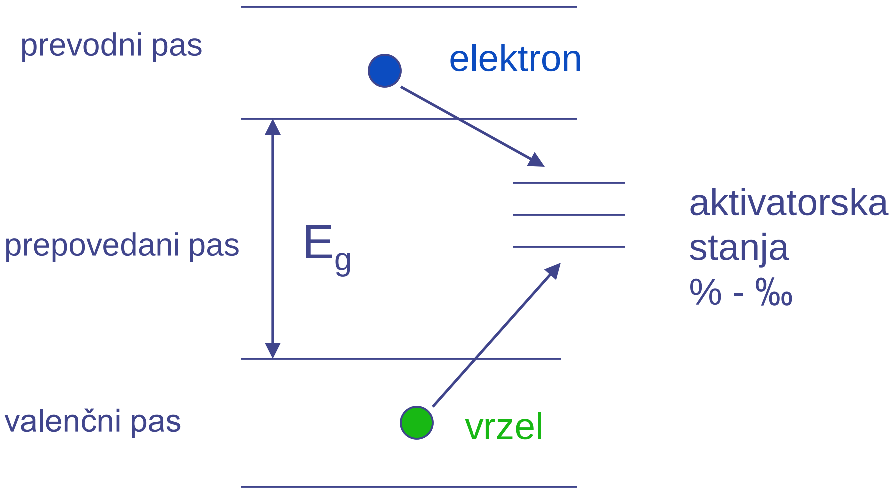
I) SCINTILATORJI

luminescenca
- fluorescenca $\tau \cong 10^{-8}$ s
- fosforescenca $\tau > 10^{-6}$ s

1.MEHANIZEM PRODUKCIJE IN VRSTE SCINTILATORJEV

A) Anorganski kristali (velik Z, $\rho \cong 4$ -7 g/cm^3)

- e-h se nevtralizirata preko aktivatorskih stanj in pri tem nastane foton
- $h\nu < E_g$, zato je kristal prozoren



\+ velika gostota in visoko vrstno število
- $\tau_d > 200$ ns
- higroskopični (razen BGO in BaF_2)

primeri: NaI(Tl), CsI(Tl), BaF_2 in BGO ($Bi_4Ge_3O_{12}$)

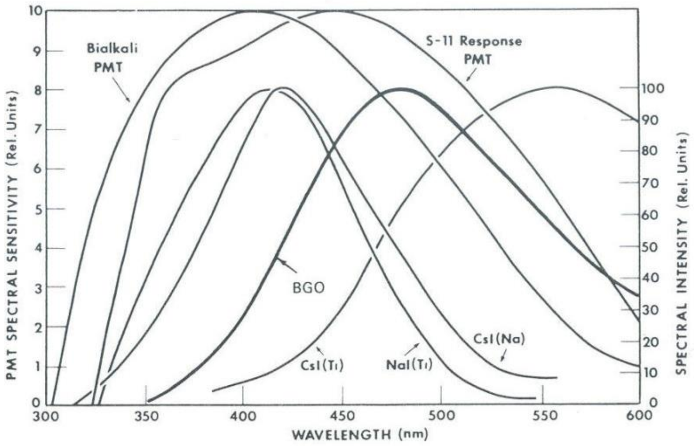


Figure 8-7 The emission spectra of several common inorganic scintillators. Also shown are the response curves for two widely used photocathodes. (Primarily from *Scintillation Phosphor Catalog*, The Harshaw Chemical Company. The emission spectrum for BGO is from Ref. 55.)

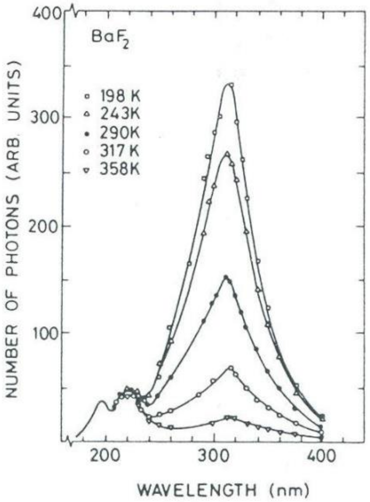


Figure 8-13 The scintillation emission spectra from BaF$_2$ measured at various temperatures. The fast component (corresponding to the two small peaks at the left) does not display the strong temperature dependence of the slow component. (From Schotanus et al.[75, 76])

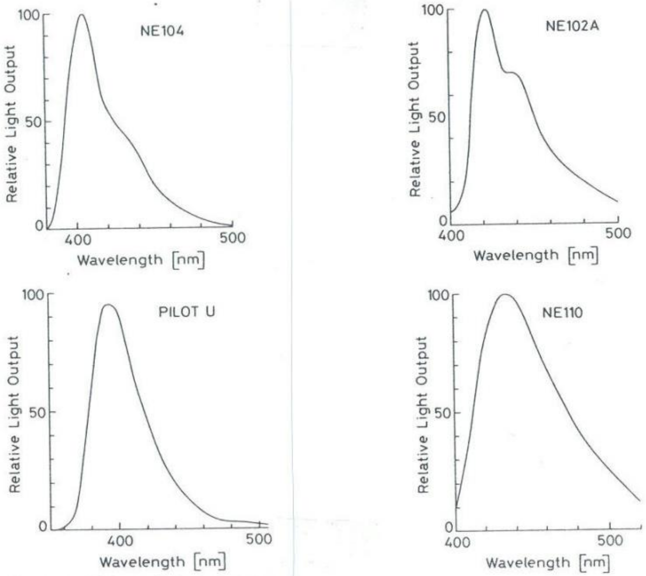


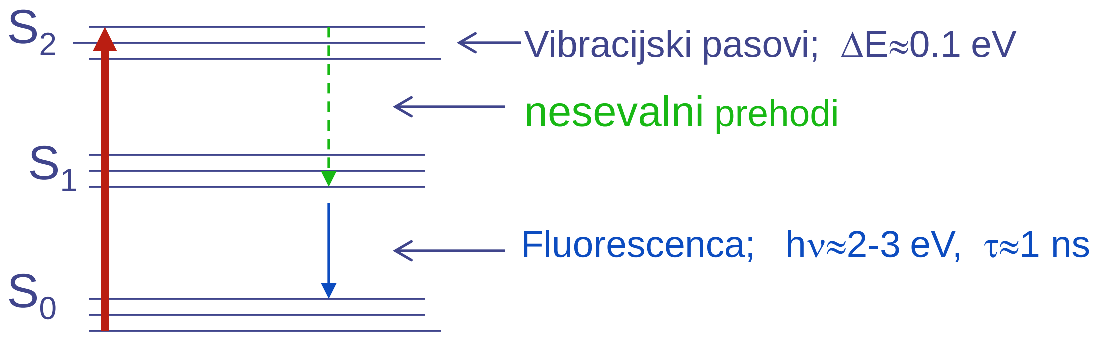
Fig. 7.5. Light emission spectra for several different plastic scintillators (from *Nuclear Enterprises* catalog [7.1])

Scintillator material	Density (g/cm^3)	Radiation length	Refractive index	Wavelength at peak	Decay time	Light yield (Y/MeV)
NaI (Tl)	3.67	2.59 cm	1.78	410 nm	230 ns	4.1 x10^4
CsI (Tl)	4.51	1.86 cm	1.85	550 nm	800–6000 ns	6.6 x10^4
CsI (Na)	4.51	1.86 cm	1.80	420 nm	630 ns	4.0 x10^4
$LaBr_3$ (Ce)	5.3	1.88 cm	1.9	358 nm	35 ns	6.1 x10^4
$Bi_4Si_3O_{12}$ BSO	6.8	1.15 cm	2.06	480 nm	100 ns	0.2 x10^4
$Bi_4Ge_3O_{12}$ BGO	7.1	1.12 cm	2.15	480 nm	300 ns	0.9 x10^4
$CdWO_4$	7.9	1.1 cm	2.25	495 nm	5000 ns	2.0 x10^4
$YAlO_3$ (Ce) YAP	5.5	2.9 cm	1.94	350 nm	30 ns	2.1 x10^4
$Lu_3Al_5O_7$ (Ce) LuAG	7.4	1.4 cm	1.84	420 nm	40 ns	2.6 x10^4
Gd_2SiO_5 (Ce) GSO	6.7	1.4 cm	1.87	440 nm	60 ns	0.8 x10^4
$PbWO_4$	8.3	0.89 cm	1.82	425 nm	25 ns	0.05 x10^4

B) Organski scintilatorji (nizek Z, $\rho \cong 1$ g/cm^3)

Gre za prehode v t.im. π orbitalah organske molekule

Singletna stanja (hitra komponenta)



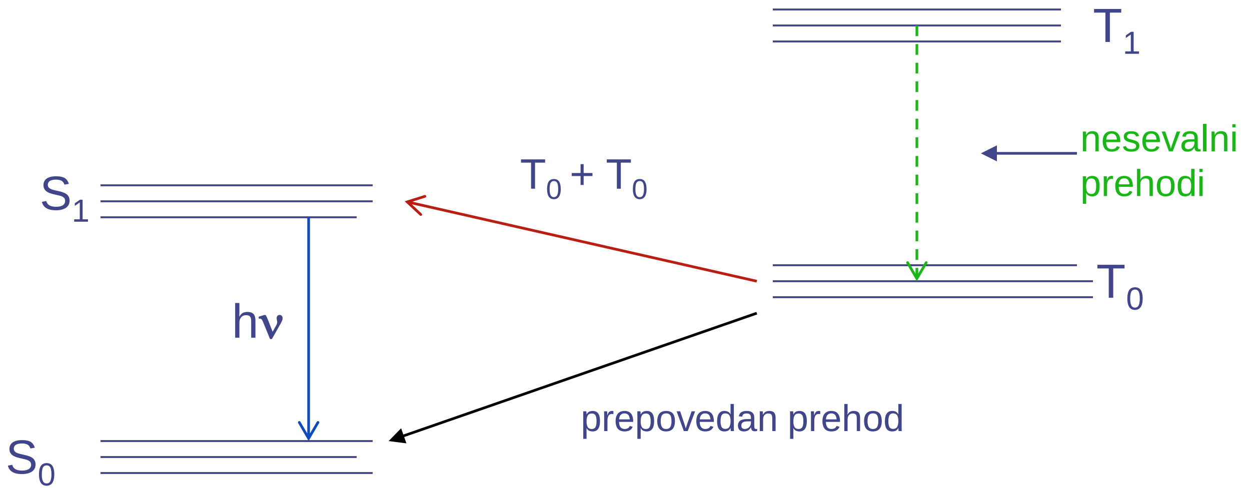
Vibracijski pasovi; $\Delta E \approx 0.1$ eV

nesevalni prehodi

Fluorescenca; $h\nu \approx 2\text{-}3$ eV, $\tau \approx 1$ ns

$h\nu < S_{10} - S_{00} \Rightarrow$
kristal je prozoren

Tripletna stanja (počasna komponenta)



$T_0 + T_0$

nesevalni prehodi

prepovedan prehod

Prehod se lahko izvrši z interakcijo dveh molekul v stanju T_0.

$T_0 + T_0 = S_1 + S_0$ + fononi

$\searrow S_0 + h\nu$

ORGANSKI KRISTALI

Antracen ($C_{14}H_{10}$) , $\tau \approx$ 30 ns, velik pridelek, za normalizacijo
Transtilben ($C_{14}H_{12}$) , $\tau \approx$ 1 ns
Naftalen ($C_{10}H_8$) , $\tau \approx$ 1 ns

-So manj v uporabi zaradi težavne obdelave (krhkost, termični šok) ter anizotropije glede na os kristala in smer vpadnega delca.

ORGANSKE TEKOČINE

- $\approx$ 3 g/l scintilatorja v topilu (ksilen, toluen, benzen, dekalin ...)
- lahko dodajo tudi ^{6}Li ali ^{10}B za termične nevtrone ali Pb za fotone (t.im.loaded liquids)
- izvor (^{14}C ali ^{3}H) zamešajo v tekočino za meritev nizkih aktivnosti β

PLASTIČNI SCINTILATORJI =

plastični polimer = (PVT-poliviniltoluen, PST-polistiren, polifenilbenzen)

+

≈10 g/l organskega scintilatorja = PBD ($C_{20}H_{14}N_2O$), p-terfenil ($C_{18}H_{14}$) ali PBO ($C_{15}H_{11}NO$)

+

fluorescenčni pretvornik (WLS) = POPOP ($C_{24}H_{16}N_2O_2$) (po potrebi)

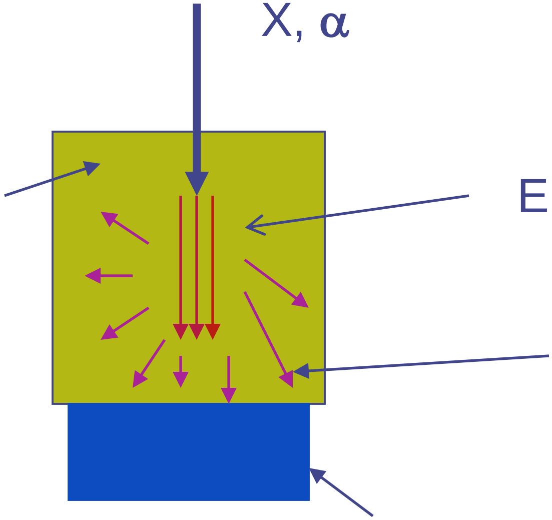
- absorbirana energija se učinkovito in hitro prenese na molekule scintilatorja, $\tau \approx$ 2-3 ns
- WLS za kompatibilnost s fotopomnoževalko
- odporni so na vodo, metilal, silikonsko olje in nižje alkohole
- telesne kisline lahko škodijo
- poceni in preprosta obdelava ⇒ široka uporaba
- proizvajalca Nuclear Enterprises (UK) in Bicron (USA)

Scintillator material	Density (g/cm^3)	Refractive index	Wavelength at peak	Decay time	Light yield (Y/MeV)
Naphtalene	1.15	1.58	348 nm	11 ns	0.4 x10^4
Antracene	1.25	1.59	448 nm	30 ns	4 x10^4
p-Therphenyl	1.23	1.65	391 nm	6 – 12 ns	1.2 x10^4
NE102™	1.03	1.58	425 nm	2.5 ns	2.5 x10^4
NE104™	1.03	1.58	405 nm	1.8 ns	2.4 x10^4
NE110™	1.03	1.58	437 nm	3.3 ns	2.4 x10^4
NE111™	1.03	1.58	370 nm	1.7 ns	2.3 x10^4
BC400™	1.03	1.58	423 nm	2.4 ns	2.5 x10^4
BC428™	1.03	1.58	480 nm	12.5 ns	2.2 x10^4
BC443™	1.05	1.58	425 nm	2.2 ns	2.4 x10^4

C) Žlahtni plini (ekscimeri)

Ekscimeri so vzbujene molekule žlahtnega plina.
Tvorijo se pri potovanju elektronov v $E > 2$ kV/cm.
Razpadejo z emisijo UV fotona: $E(\mathrm{Xe}) \approx 7.5$ eV, $E(\mathrm{Kr}) \approx 8.5$ eV, $E(\mathrm{Ar}) \approx 10$ eV, $\Delta E \approx 1$ eV.

Za Xe velja: $dN_f/dx \approx 100\ (\mathrm{fot/kV})\ E\ -\ 100\ (\mathrm{fot.\ cm/kp})\ p$



X, α

Xe, Ar
ali Kr

Elektroni v E= 5 kV/cm

UV fotoni

Detektor scintilacij (npr. FP ali VŽPK+TMAE ali TEA)

\+ boljša energijska ločljivost kot VŽPK $(\sigma_E / E \rightarrow \{F/N_e\}^{1/2})$
\- počasen ($\tau \approx 1\ \mu s$)
\+ zaradi velike površine lahko konkurira polprevodniškim detektorjem

2. PRIDELEK FOTONOV

Pridelek fotonov (photon yield)
L = L (vrste scintilatorja, energije delca, vrste delca, temperature, ...)

približno velja $L \propto E$

Za elektrone in žarke gama:

NaI(Tl)	25 eV/foton (10% izkoristek)
Antracen	60 eV/foton
Plastik	100 eV/foton
BGO	300 eV/foton (1% izkoristek)

- za težje delce (p,d,α) je izkoristek še slabši
- če upoštevamo še izgube pri zbiranju fotonov na fotokatodi ter kvantni izkoristek ugotovimo, da potrebujemo 10 x več energije za 1 fotoelektron.
- v plinu potrebujemo $\approx$30 eV za ionski par,
v polprevodniku pa le 2-3 eV za e-h.

Odmik od linearnosti opiše t.im. Birksova formula:

$$\boxed{dL/dx = (A\, dE/dx) / (1 + k_B\, dE/dx)}$$

Popravke je treba upoštevati zlasti za organske scintilatorje in težje delce.

Če $k_B\, dE/dx \ll 1 \Rightarrow dL/dx \propto dE/dx \Rightarrow L \propto E$ i.e. linearnost

To velja za elektrone z energijo nad 125 keV v organskem scintilatorju.

Za protone z energijo pod 5 MeV pa približno velja $L \propto E^{3/2}$ in linearnost se začne šele pri višji energiji.

Če $k_B\, dE/dx \gg 1 \Rightarrow dL/dx = A/kB \Rightarrow L \propto$ doseg
(nasičenje)

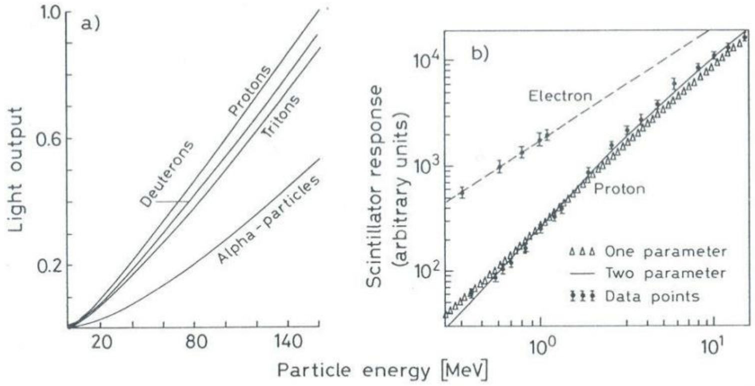
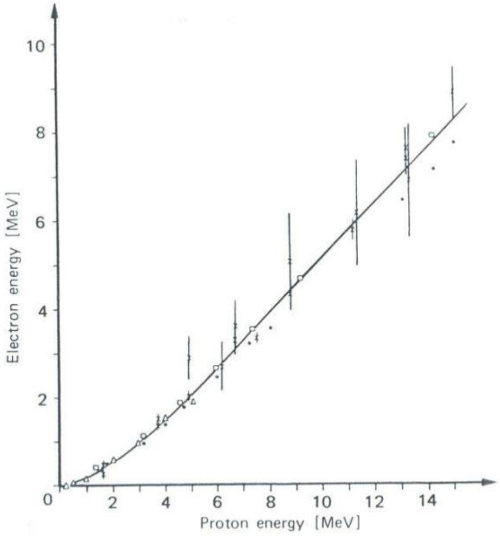


Fig. 7.8 a, b. Response of NE102 plastic scintillator to different particles ((**a**) from *Gooding* and *Pugh* [
(**b**) from *Craun* and *Smith* [7.7])

Figure 8-4 The light output (expressed in equivalent electron energy deposition) versus proton energy for liquid scintillator NE 213. (From Maier and Nitschke.[29])



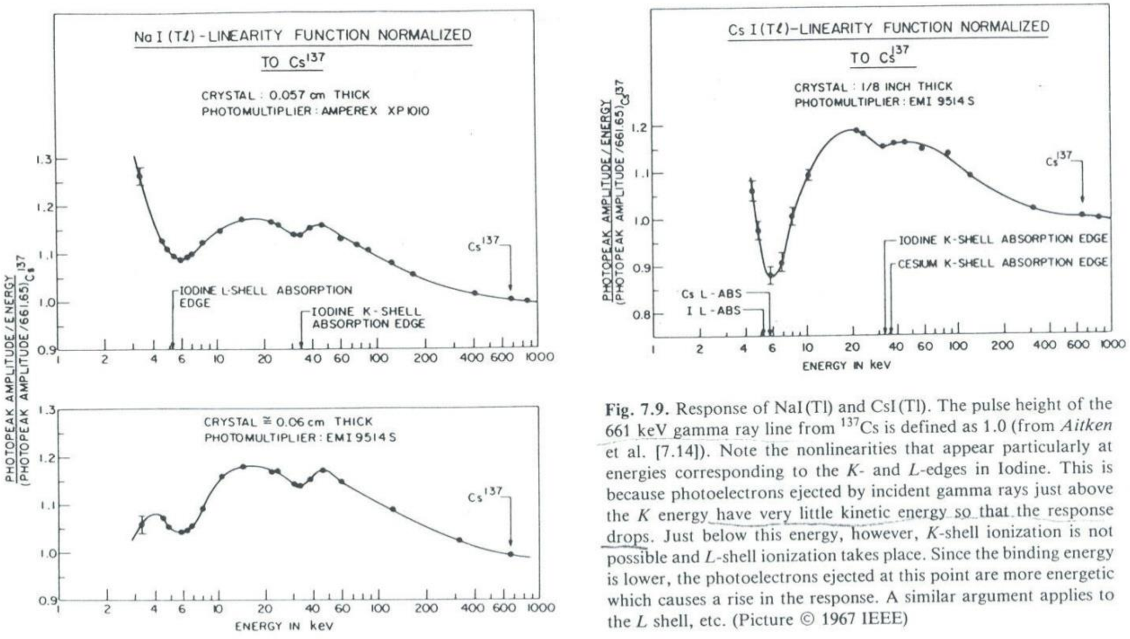


Fig. 7.9. Response of NaI(Tl) and CsI(Tl). The pulse height of the 661 keV gamma ray line from ^{137}Cs is defined as 1.0 (from *Aitken* et al. [7.14]). Note the nonlinearities that appear particularly at energies corresponding to the *K*- and *L*-edges in Iodine. This is because photoelectrons ejected by incident gamma rays just above the *K* energy have very little kinetic energy so that the response drops. Just below this energy, however, *K*-shell ionization is not possible and *L*-shell ionization takes place. Since the binding energy is lower, the photoelectrons ejected at this point are more energetic which causes a rise in the response. A similar argument applies to the *L* shell, etc. (Picture © 1967 IEEE)

Temperaturna odvisnost pridelka fotonov L

- za organske scintilatorje ni hude odvisnosti L od T; L(60^0 C)/L(20^0 C) ≈ 0.95
- za BGO (1/L)(dL/dT) ≈ - 1% / ^{o} C
- za BaF_2 je hitra komponenta neodvisna od T, za počasno pa je dL/dT < 0
- za $PbWO_4$ je (1/L)(dL/dT) ~ -2 % / ^{0} C ⇒ termostatiranje v kalorimetrih

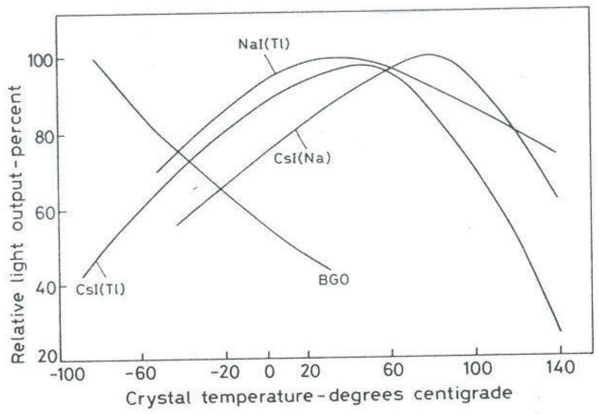


Fig. 7.10. Temperature dependenc of light output from inorganic crys tals (from *Harshaw Catalog* [7.3])

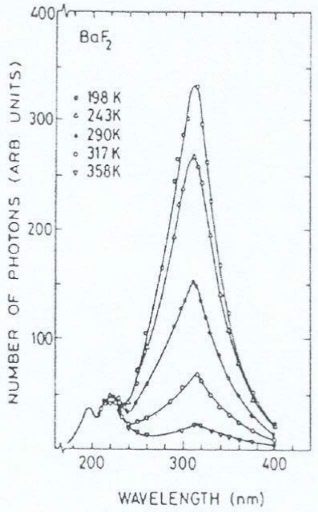
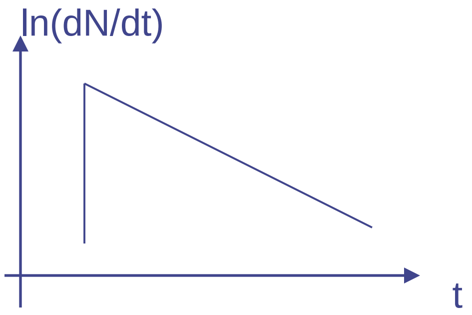
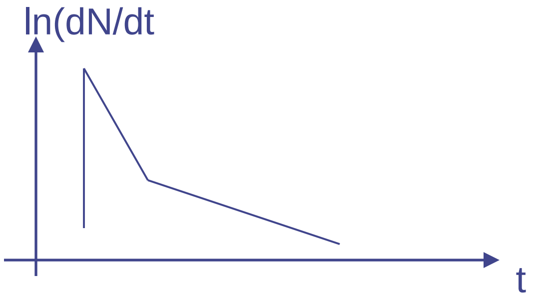


Figure 8-13 The scintillation emission spectra from BaF_2 measured at various temperatures. The fast component (corresponding to the two small peaks at the left) does not display the strong temperature dependence of the slow component. (From Schotanus et al.[75,76])

3. ČASOVNI POTEK SCINTILACIJ



- vzbujena stanja se tvorijo zelo hitro (< 1 ns)
- razpadni časi so $\tau \approx 10^{-9} – 10^{-6}$ s



- nekateri scintilatorji imajo dve časovni komponenti :

$$dN/dt = A \exp(-t/\tau_1) + B \exp(-t/\tau_2)$$

- ponekod je treba upoštevati počasno tvorbo scintilacij :

$$dN/dt = I_0 [\exp(-t/\tau_1) - \exp(-t/\tau_2)]$$

- časovni potek scintilacij je občutljiv na nečistoče in temperaturo
- pri scintilacijah z dvema komponentama je možna diskriminacija glede na vrsto delca. Pridelek vsake komponente posebej je odvisen od dE/dx. Različni delci imajo različne dE/dx in zato različen potek scintilacij (slike!).

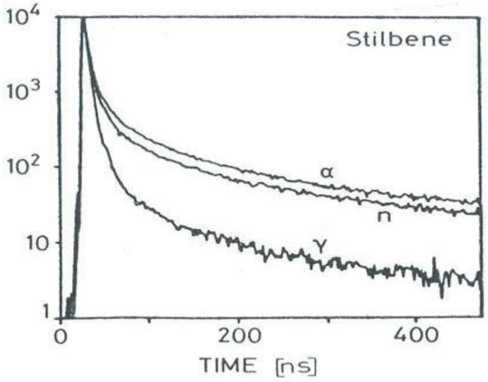


Fig. 7.11. Pulse shape of stilbene light for alpha particles, neutrons and gamma rays (from *Lynch* [7.71]; picture © 1975 IEEE)

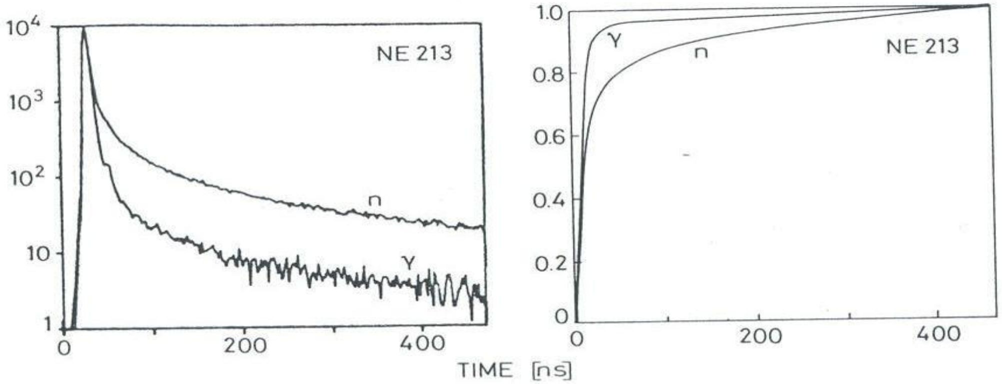


Fig. 7.12. Pulse shape differences of NE213 liquid scintillator light for neutrons and gamma rays. The time integral of the light pulses is also shown. A discrimination between these radiations may be obtained by measuring the time it takes for the integrated pulse to reach a certain fixed level (from *Lynch* [7.17]; picture © 1975 IEEE)

4. ZBIRANJE SVETLOBE IZ SCINTILATORJA NA FP

IZGUBE FOTONOV

a) Lom skozi površino scintilatorja

-totalni odboj $\sin(\theta_t) = n_z / n_{sc}$, $n_z = 1$ $n_{sc} = 1.5 \Rightarrow \theta = 42^0$

signal je lahko odvisen od mesta absorpcije (za majhne scintilatorje je to zanemarljivo)

-odboj na zunanjem reflektorju

- Al folija + maksimalen totalni odboj, $\theta \rightarrow$ min $n_z \rightarrow 1$

  pustiti zrak med scintilatorjem in reflektorjem

- difuzni odboj na površini, bela barva ali prah (MgO, TiO_2 , AlO_2),

  odbojnost odvisna od λ (slika !)

- difuzni reflektorji so v splošnem malo boljši

b) Atenuacija (za dolge scintilatorje)

$L(x) = L_0 \exp(-x/l)$, l = atenuacijska dolžina $\geq$ 1 m

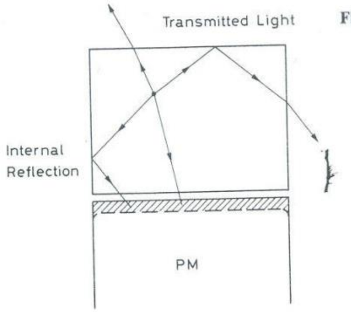


Fig. 9.1. Light collection in a typical scintillator

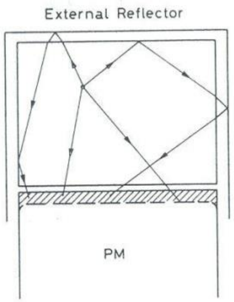


Fig. 9.2. Scintillator with an external reflector for improved light collection

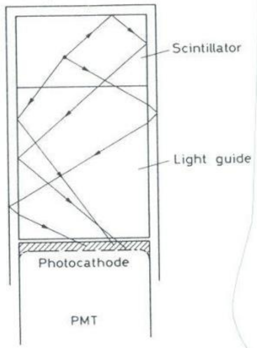


Fig. 9.5. Example of scintillator-PM coupling with a light guide

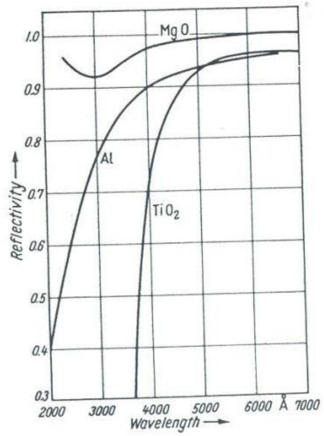


Fig. 9.3. Reflectivity of various materials (from *Mott* and *Sutton* [9.1])

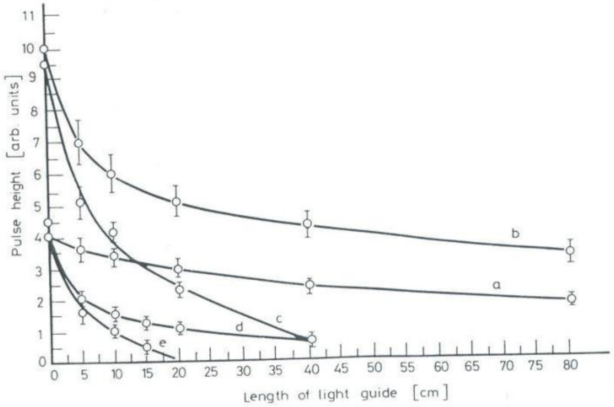


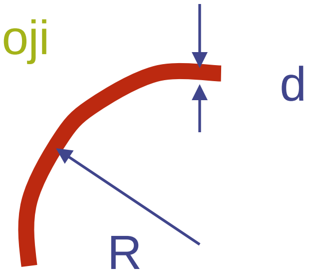
Fig. 9.8. Performance of a scintillation detector using light guides of varying lengths and different reflection schemes (from *Kilvington* et al. [9.5]): (*a*) total internal reflection only, no reflector, (*b*) total internal reflection with external reflector, (*c*) light guide painted with diffuse reflector, (*d*) specular reflector, no light guide, (*e*) diffuse reflector, no light guide

c) povezava s fotopomnoževalko

- tesen stik brez zraka zahteva zelo ravne površine
- vmesnik s podobnim lomnim količnikom (silikonska mast, olje ali guma za organske scintilatorje)

Svetlobni vodniki

- če ni prostora za FP ali če je magnetno polje, vodimo svetlobo do FP s svetlobnim vodnikom iz stekla pleksi s totalnimi odboji
- adiabatske oblike = majhne ukrivljenosti (R » d)
- gostota toka fotonov se ohranja.



Površina stranice scintilatorja naj bo enaka površini FP.

$$L_{FP} / L_{scint} \le S_{FP} / S_{scint}$$

- oblike svetlobnih vodnikov (slike !)
- optična vlakna so bolj fleksibilni svetlobni vodniki (majhen d).

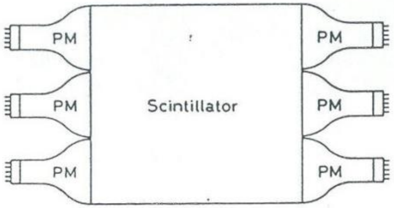


Fig. 9.4. A large scintillator viewed by PM's for better light collection efficiency

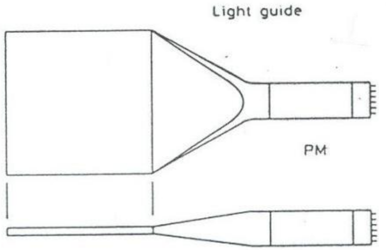


Fig. 9.6. Adapting a flat scintillator sheet to the circular face of a PM with a light guide

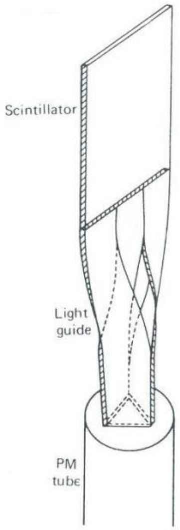


Figure 8-16 A strip light guide can be used to couple the edge of a large, flat scintillator to a PM tube.

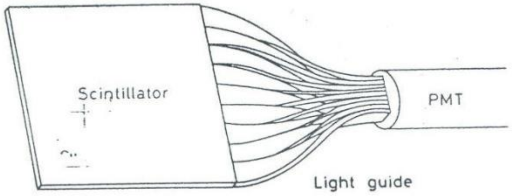


Fig. 9.7. The *twisted* light guide. Many strips of light guide material are glued on to the edge of the scintillator and then twisted 90° so as to fit onto the PM face

Fluorescenčni pretvorniki - WLS

- pri kalorimetriji je veliko scintilatorjev
velike površine ⇒ veliko FP ⇒ drago + veliko prostora
- rešitev: svetlobni vodniki dopirani z WLS
(pogosto se uporablja BBQ; absorbira modro, seva zeleno)
- sklopitev preko zračne reže ali z optičnim oljem
- precejšnje izgube vendar zberejo svetlobo iz vseh robov (slike!)

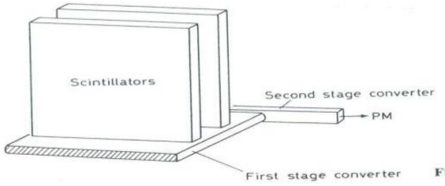


Fig. 9.9. Fluorescent converter set-up

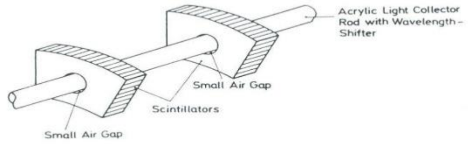


Figure 8-17 Sections of two slab scintillators are shown coupled to a common light pipe loaded with wavelength shifter. Light passing across the air gap and entering the pipe can be absorbed, reradiated, and guided to the ends of the rod. (From Eckardt et al.[101])

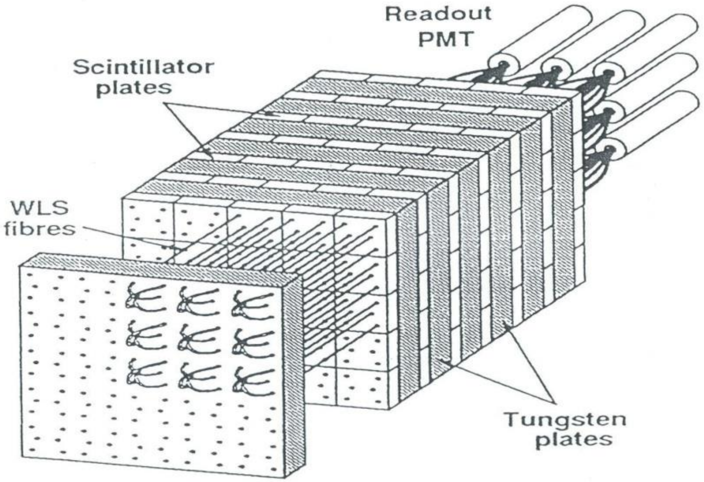


Figure 89: *Schematic view of the shashlik module.*

II) Detekcija svetlobe

1) Fotopomnoževalke (klasične)
2) Večanodne fotopomnoževalke in mikrokanalne plošče
3) Fotodiode
4) Plinski detektorji svetlobe

1) Fotopomnoževalka

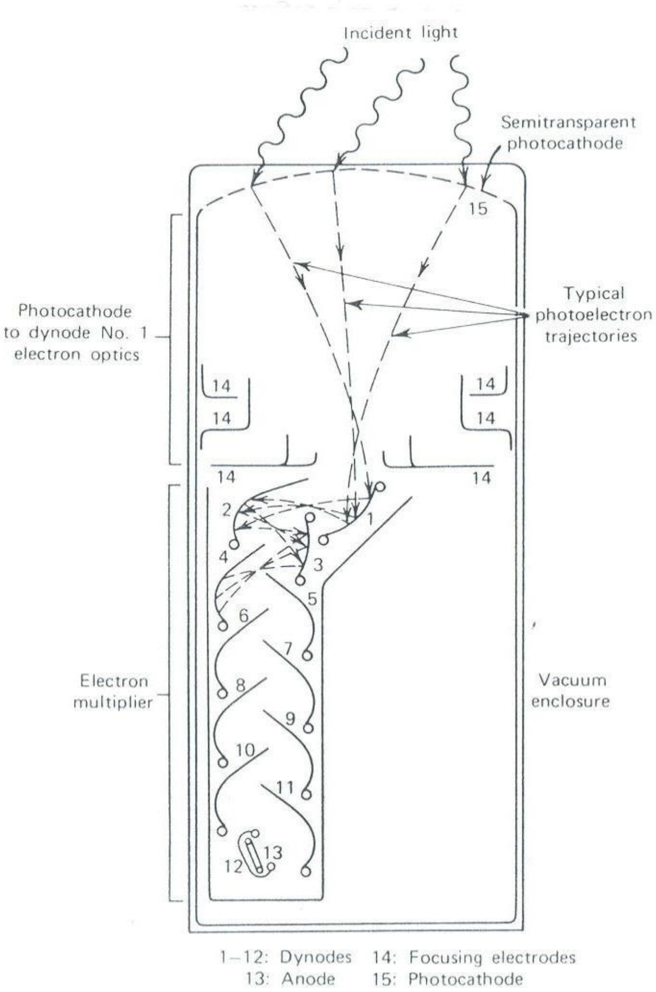
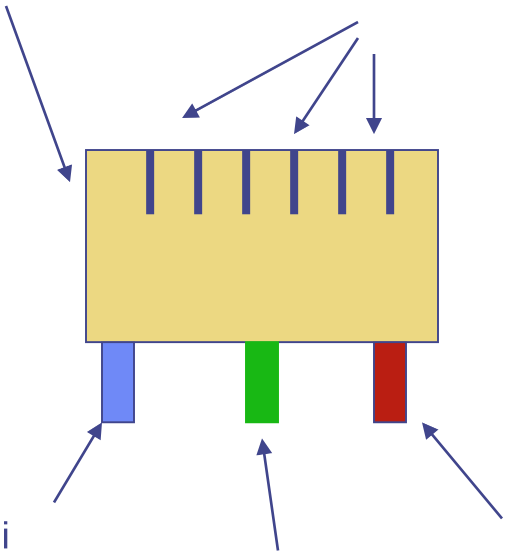


Figure 9-1 Basic elements of a PM tube. (From Ref. 1.)

+



BAZA
(uporovna veriga etc)

kontakti za fotokatodo
in dinode

anodni
signal

zadnja dinoda

visoka napetost

1) meritev sunkov
2) meritev toka

Fotokatode

- Fotoefekt : $E_e = h\nu - \Phi$

maksimalna energija elektrona

energija fotona

izstopno delo (energija praga)

- kvantni izkoristek (Quantum Efficiency)

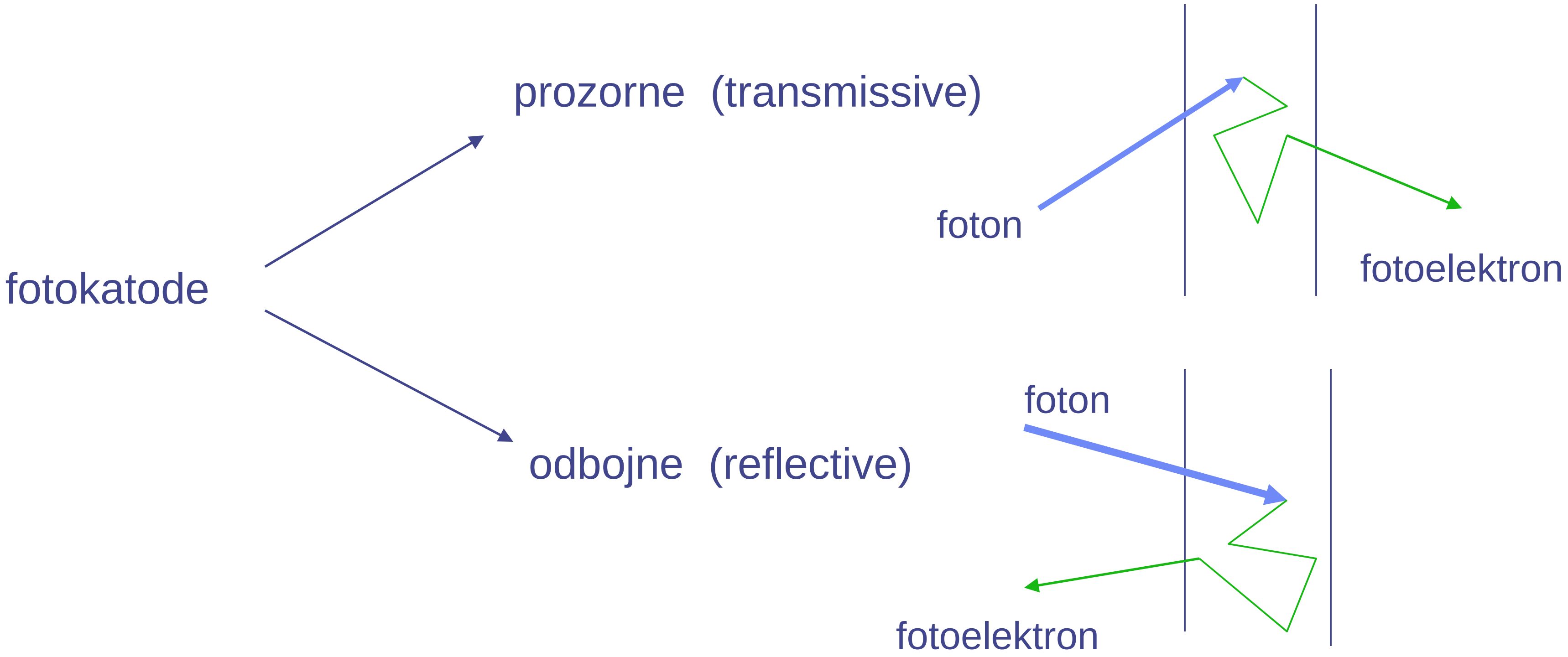
$$\eta(\lambda) = \frac{\text{število fotoelektronov iz katode}}{\text{število vpadnih fotonov}}$$

ali sevalna občutljivost katode $E(\lambda) = \dfrac{I_k}{P(\lambda)}$

tok fotoelektronov iz katode (A)

vpadna sevalna moč (W)

$$\eta(\lambda) = \frac{I_k / e_o}{P(\lambda)/h\nu} = \frac{hc}{\lambda e_0} E(\lambda)$$



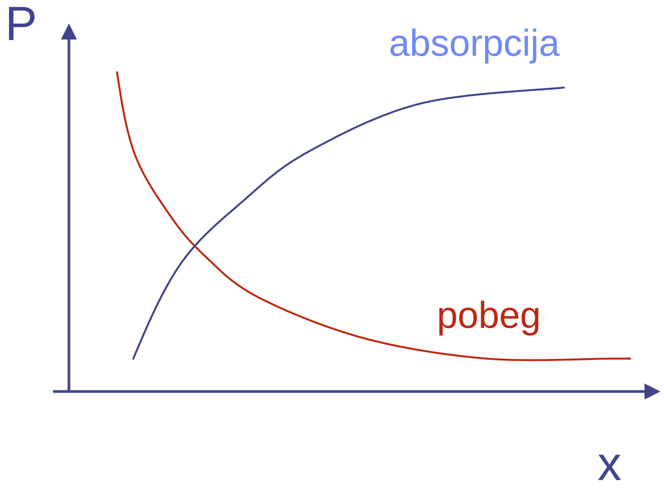
fotokatode

prozorne (transmissive)

odbojne (reflective)

<u>Kvantni izkoristek je produkt</u> :

- verjetnosti za transmisijo skozi vstopno okno
- verjetnosti za absorpcijo in fotoefekt
- verjetnosti za izstop fotoelektrona iz katode
  $\Rightarrow$ obstaja optimalna debelina fotokatode



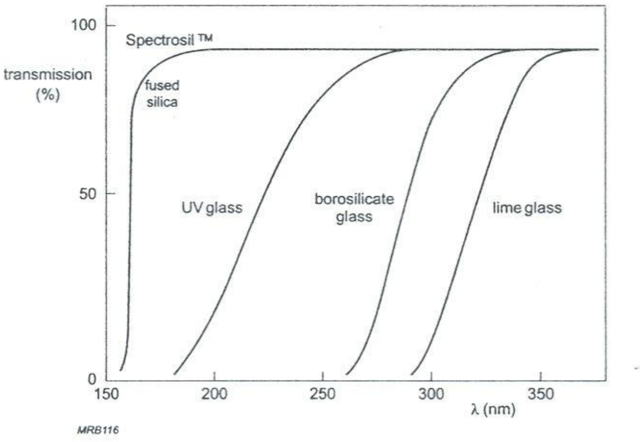


Fig.1.5 Transmission (%) as a function of wavelength λ for various glasses used in photomultiplier input windows (thickness 3 mm)

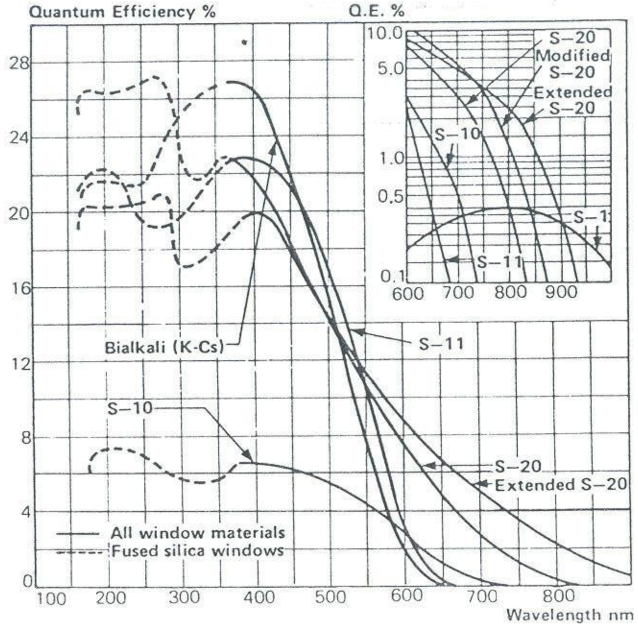
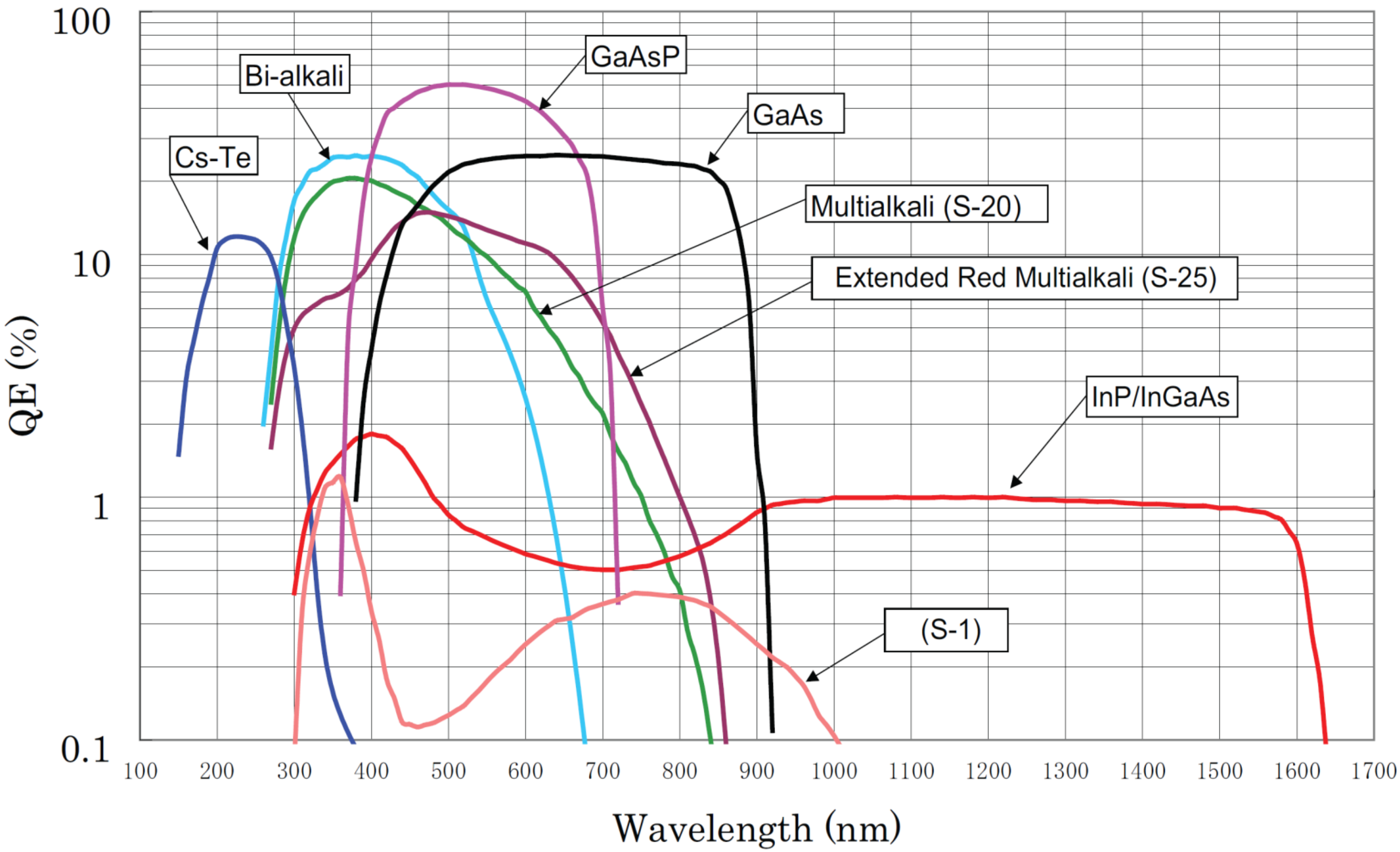


Fig. 8.2. Quantum efficiency of various photocathode materials (from *EMI Catalog* [8.2])

Table 8.1. Photocathode characteristics (from RTC catalog [8.3])

Cathode type	Composition	λ at peak response [nm]	Quantum efficiency at peak
S1 (C)	Ag − O − Cs	800	0.36
S4	SbCs	400	16
S11 (A)	SbCs	440	17
Super A	SbCs	440	22
S13 (U)	SbCs	440	17
S20 (T)	SbNa − KCs	420	20
S20R	SbNa − KCs	550	8
TU	SbNa − KCs	420	20
Bialkali	SbRb − Cs	420	26
Bialkali D	Sb − K − Cs	400	26
Bialkali DU	Sb − K − Cs	400	26
SB	Cs − Te	235	10

Quantum efficiency



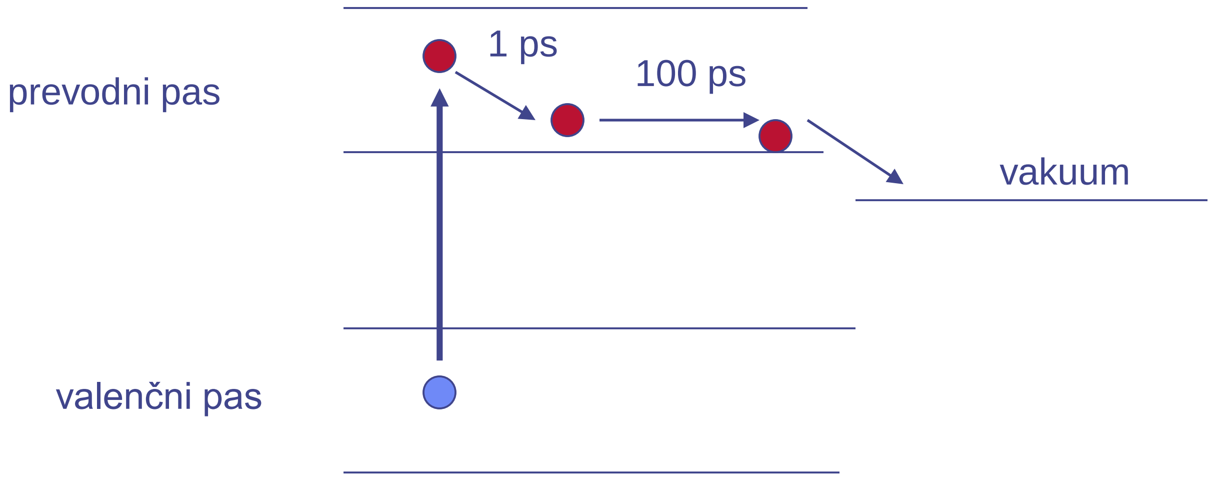
večinoma so fotokatode polprevodniki

antimon (Sb) + alkalne kovine (K, Cs, Rb, Na ...)

- zaradi zasedenosti stanj v polprevodniku izgublja fotoelektron manj energije pri trkih z ostalimi elektroni in zato lažje pride do površine (vezani elektroni imajo veliko maso, zato je manj izgube energije), $\eta = 10 – 30$ %.

- v kovinah so velike izgube zaradi trkov s prostimi elektroni ($\eta \approx 0.1$ %) .

- galijev fosfid (GaP), dopiran z Zn+Cs, ima negativno "elektronsko afiniteto" (negative electron afinity) za elektron v prevodnem pasu, $\eta \approx 80$ %.



Sistem zbiranja fotoelektronov

- večinoma uporabljajo električno polje med fotokatodo in prvo dinodo (ponekod tudi magnetno polje)

Zahteve:

- velik izkoristek zbiranja fotoelektronov (različne poti, izstopne energije in različne smeri).

- izkoristek naj bo čimmanj odvisen od mesta nastanka QE(r)

- čas potovanja od fotokatode do prve dinode naj bo čimmanj odvisen od mesta nastanka, ker to prispeva k časovni ločljivosti ($\Delta t \approx 0.3$ ns)

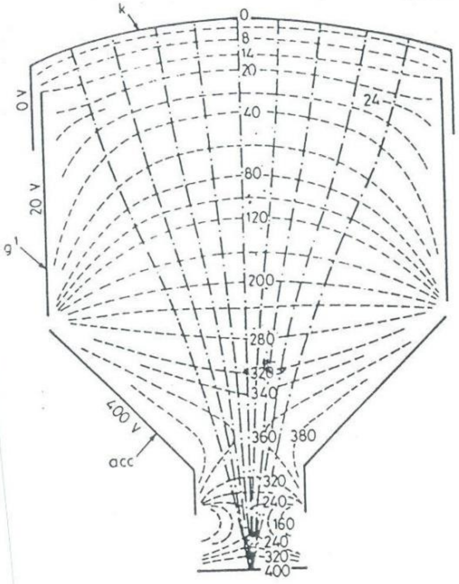


Fig. 8.15. Equipotential lines in the ele
tron-optical input system of a fast phot
multiplier (from *Hull* [8.9])

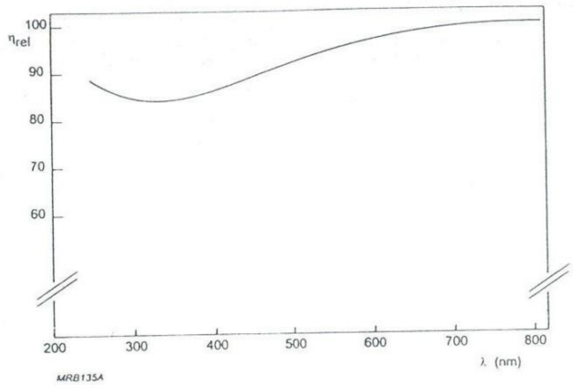


Fig.2.2 Example of relative input system collection efficiency as a function of wavelength

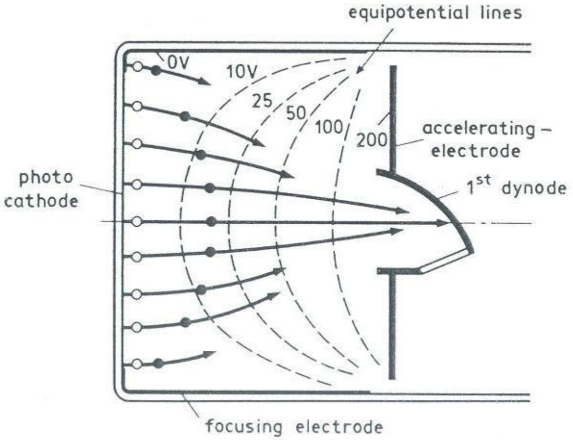
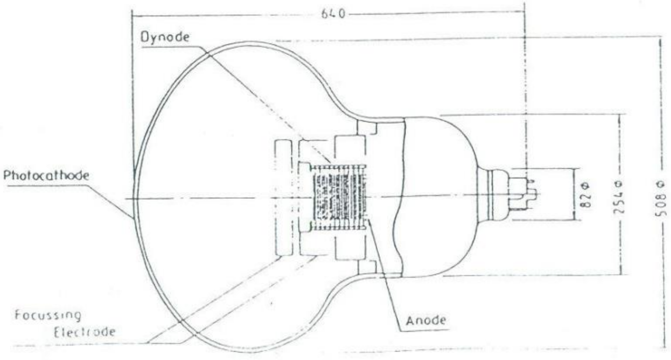


Fig. 8.14. Transit time difference (from *Schonkeren* [8.1])

Fig. 4.2. Section through photomultiplier tube R 1449 with a spherical photocathode of 508 mm diameter [KU 83].



Pomnoževalni sistem (dinode)

- sekunadarna emisija na dinodah, $\delta \approx 3\text{-}5$

- dinode iz polprevodnikov in izolatorjev (isti razlog kot za fotokatode)

- polprevodnik na prevodni podlagi, ker potrebujemo E za pospeševanje

- lahko tudi zlitina (Ag-Mg, Cu-Be, Cs-Sb).
  Alkalna kovina na površini oksidira in tvori izolatorsko plast.

Zahteve:

- veliko pomnoževanje, faktor sekundarne emisije δ
- stabilnost pri velikih tokovih
- nizka termična emisija (šum)

- 10-14 dinod → $G = 10^7\text{-}10^8$
- GaP dinode → 5 dinod → isti G

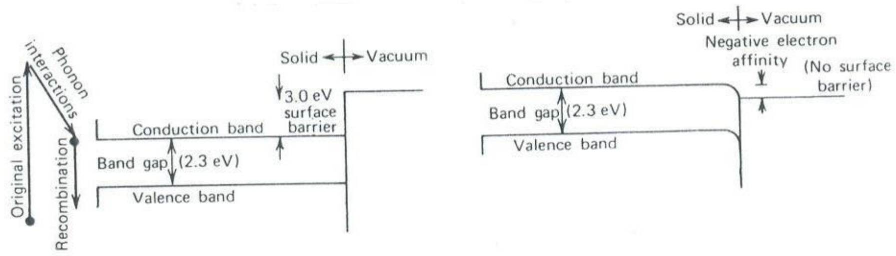


Figure 9-4 Band structure near the surface for conventional semiconductors (left) and NEA materials (right). (Adapted from Krall et al.[7])

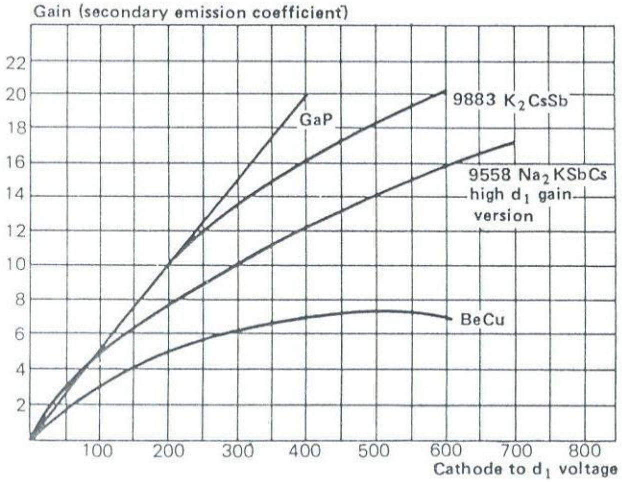


Fig. 8.9. Secondary emission factor for several dynode materials (from *EMI Catalog* [8.2])

konfiguracija dinod

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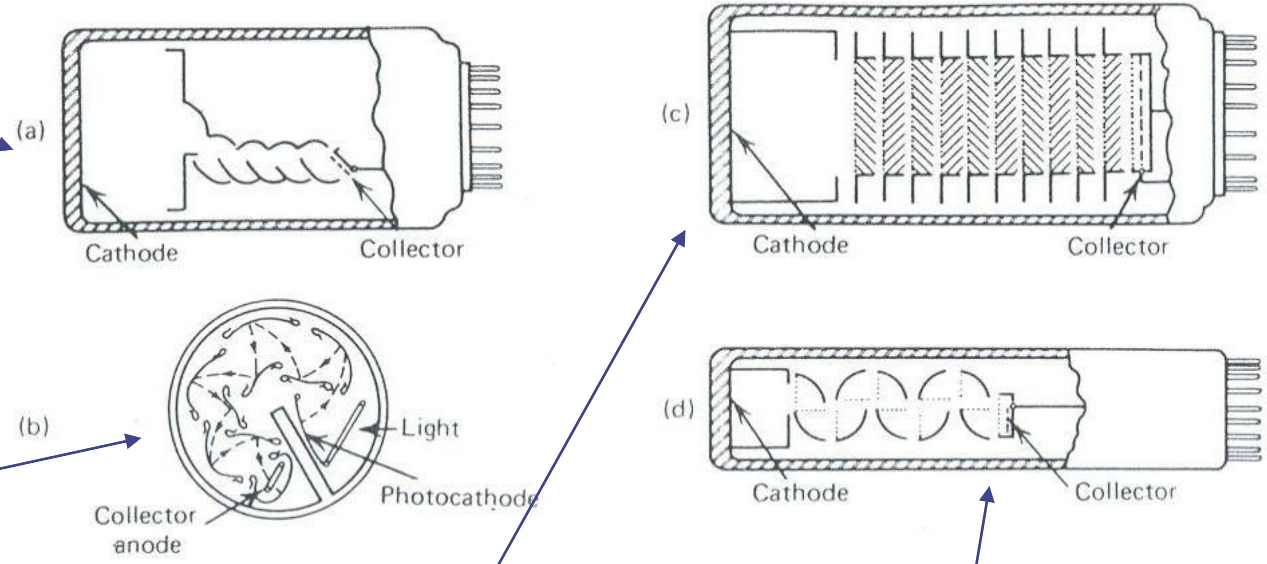
PHOTOMULTIPLIER TUBES AND PHOTODIODES



Linear focused

circular

“venetian blind”

“box grid”

Figure 9-7 Configurations of some common types of PM tubes. (a) Focused linear structure. (b) Circular grid. (c) Venetian blind. (d) Box-and-grid. (Courtesy of EMI GENCOM Inc., Plainview, NY.)

Delilniki napetosti

- napetost na dinodah vzdržujemo z uporovno verigo skozi katero teče tok I_R
- med fotokatodo in elektrodo za fokusiranje je potenciometer za optimizacijo zbiranja
- anodni tok I_a vpliva na spremembo dinodne napetosti in s tem ojačenja G:

$$\Delta G/G \approx I_a/I_R \quad \Longrightarrow \quad I_a \approx I_R/100 \text{ za } \Delta G/G \approx 1\%$$

- zadnje dinode opremimo s kondenzatorji, v katerih je shranjen naboj za tokovni sunek ali z Zener diodami, ki vzdržujejo napetost.
- napetost na fotokatodi
  - -anoda ozemljena
  - - puščanje toka skozi steklo na ozemljene dele (baza,scintilator) (elektroluminesc.)
  - - ni potreben sklopitveni kondenzator
  - - uporabno za hitre pulze, timing
- variacije VN se preko kondenzatorja prenašajo na izhod v primeru, da je anoda na visoki napetosti in katoda ozemljena

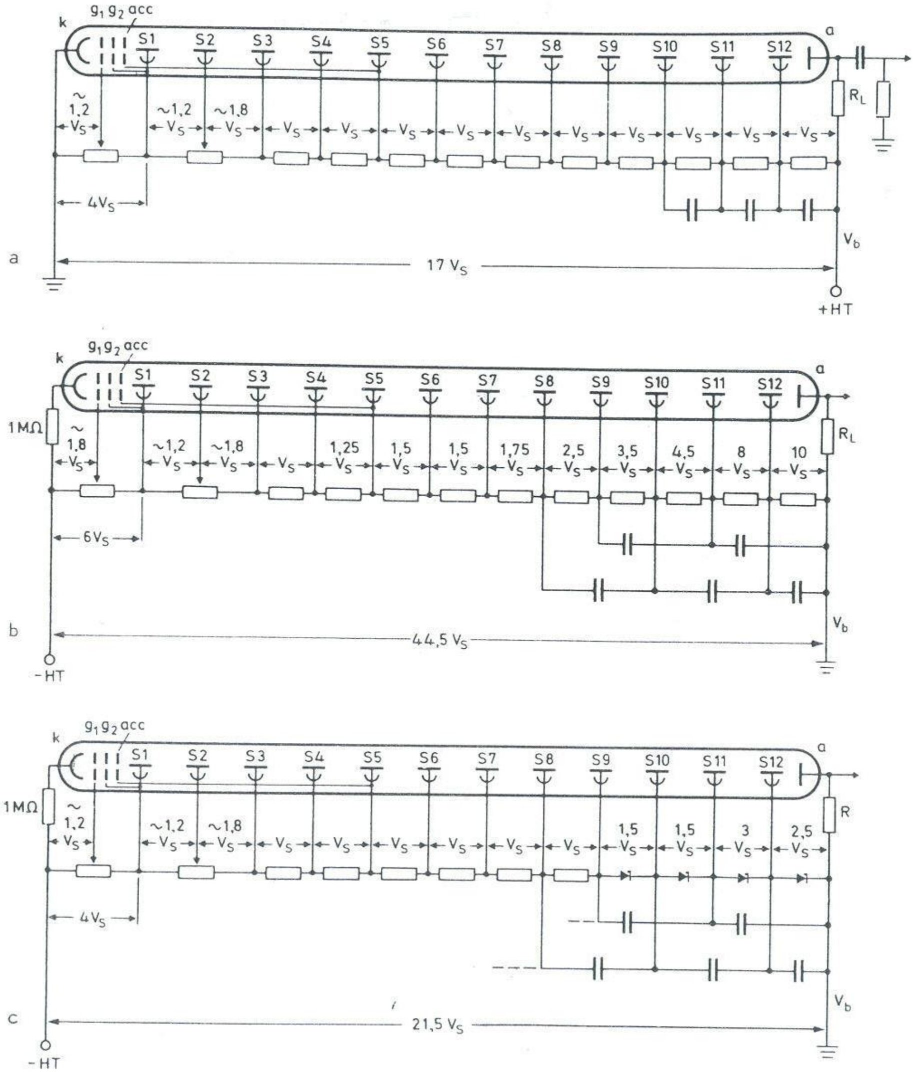


Fig. 8.10 a – c. Examples of PM voltage divider networks (after examples from *Philips Catalog* [8.7]: (**a**) divider network using positive high voltage; note the AC coupling capacitor at the anode, (**b**) a network using negative high voltage and decoupling capacitors for maintaining the voltages between the last few dynodes, (**c**) example of the use of zener diodes to maintain voltages on the last few dynodes

Visoka napetost

G...pomnoževalni faktor FP
δ...faktor sekundarne emisije
n...število dinod
U_d..napetost med dinodama
U...celotna napetost na FP

Približno velja:

$G = \delta^n$ $\delta = k\,U_d$ in $U = n\,U_d$

Odtod sledi:

$G \approx k^n\,U^n/n^n$ in $dG/G \approx n\,dU/U$

Pri n=10 in $dU/U \approx 0.1\ \%$

dobimo $dG/G \approx 1\ \%$,

torej potrebujemo
stabilizirano napetost.

Porazdelitev višin signalov enega fotoelektrona

Variacija pomnoževanja:

- statistična narava sekundarne emisije
- variacija sekundarne emisije po površini dinode
- različne energije fotoelektrona
- različni koti izstopa iz fotokatode

Meritev:

a) šibka osvetlitev in

b) integracija izhodnega signala (meritev naboja)

Porazdelitev Polya približno opiše spekter enega fotoelektrona.

$$P(q) = \frac{1+\Theta}{q_{av}\,\Gamma(1+\Theta)} \left[\frac{(1+\Theta)q}{q_{av}} \right]^{\Theta} \exp - \left[(1+\Theta)q/q_{av} \right]$$

$\Theta = 0.113\, q_{av} - 0.095$, $\quad q_{av}$ (fC)

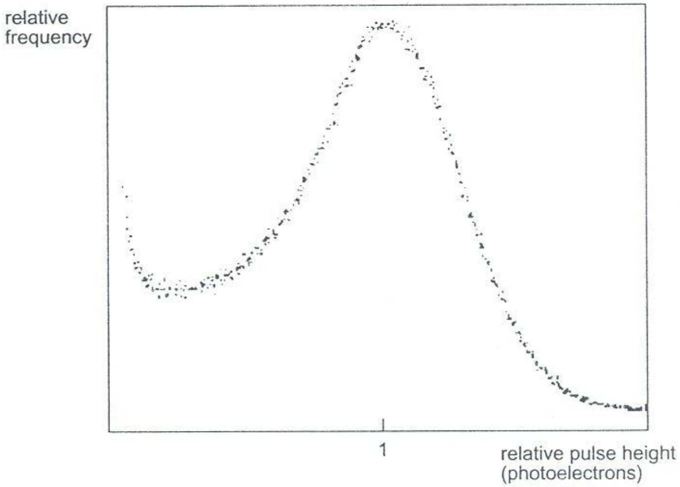


Fig.2.4 Typical single-electron spectrum. Resolution 67% FWHM.
Peak-to-valley ratio 2.8:1

- enaka porazdelitev v VŽPK

- konvolucija za več fotoelektronov

$\sigma_N/N \approx \sigma_1/(N_{f.e.})^{1/2}$

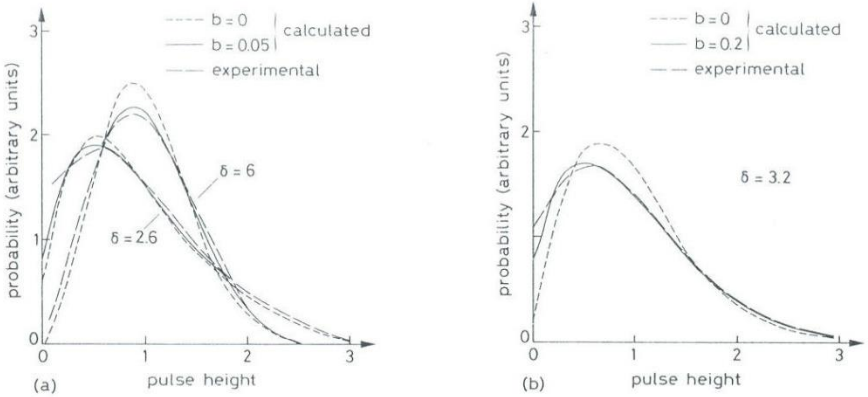


Fig. 8.8. Single-electron spectra for **(a)** linear-focused PM, **(b)** venetian blind PM (from *Schonkeren* [8.1])

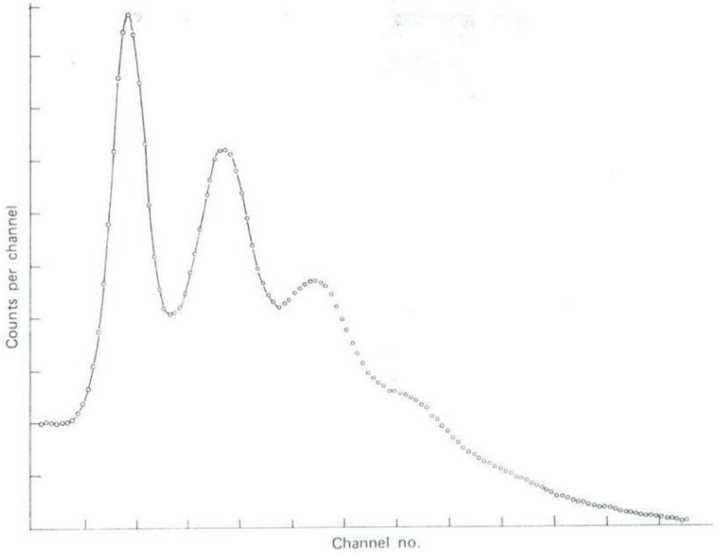


Figure 9-6 The measured pulse height spectrum for weak scintillation events obtained from a RCA 8850 photomultiplier tube. The high-gain first dynode results in distinguishable peaks in the spectrum corresponding to 1, 2, and 3 photoelectrons per pulse. (From Houtermans.[12])

Šum fotopomnoževalke

(temni tok = enolelektronski sunki)

1) termična emisija iz katode in dinod
(največji prispevek)

$I \propto T^2 \exp(-e\phi/kT)$, Richardson

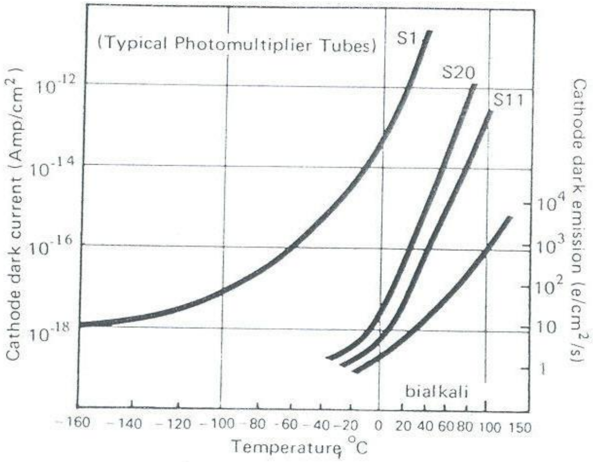


Fig. 8.19. Dark noise vs. temperature for various photocathodes (from *Wardle* [8.10])

2) tok iz kontaktov na bazi (“leakage”)

3) radioaktivna kontaminacija fotopomnoževalke lahko direktno izbije elektrone iz dinod ali povzroči fluorescenco v steklu.

“afterpulsing”

- Ionizacija residualnega plina v FP. Ioni se vrnejo na katodo, kjer izbijejo nov fotoelektron: $\Delta t \approx$ 100 ns – 1 μs
- “electrode glow”: zadnje dinode lahko sevajo svetlobo, ki pride do fotokatode in izbije nov fotoelektron; $\Delta t \approx$ 30-60 ns.

Energijska ločljivost

- statistika tvorbe fotonov pri absorpciji ionizirajočega sevanja,
- nehomogenost te pretvorbe,
- izkoristek zbiranja fotonov na fotokatodi,
- kvantni izkoristek ter homogenost QE po površini fotokatode
- izkoristek zbiranja fotoelektronov na prvi dinodi
- pomnoževanje na dinodah, kjer prevladuje statistika sekundarne emisije iz prve dinode,
- šum elektronike je ponavadi zanemarljiv.

Statistične fluktuacije bodo najbolj pomembne v tistem delu signalne verige, kjer je število nosilcev informacije najmanjše.
Pri scintilacijskih detektorjih je to število fotoelektronov na prvi dinodi.

$$R = \Delta E_{FWHM}/E \quad = \quad (\alpha + \beta E)^{1/2}/E$$

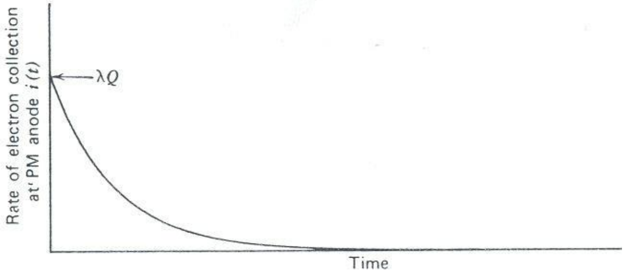
definicija ločljivosti

parametrizacija

Oblika sunkov

Fotopomnoževalka je tokovni generator

$I(t)=(GNe_0/\tau_s)\exp(-t/\tau_s)$, $GNe_0 = Q$



N...število fotoelektronov
G...pomnoževalni faktor
Q...naboj v sunku
τ_s ...razpadni čas vzb. stanj v scintilatorju

R in C ... upornost in kapaciteta anode vključno z izhodno upornostjo in kapaciteto kablov.

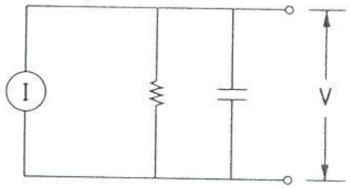


Fig. 8.12. Equivalent circuit for a photomultiplier. The PMT may be considered as an ideal current generator in parallel with a certain resistance and capacitance

Enačba:

$I = U/R + C\, dU/dt$

Rešitev:

$$U(t) = -(Q/C)\,[RC/(RC - \tau_s)]\,\,[\exp(-t/\tau_s) - \exp(-t/RC)]$$

Če RC>> τ_s (voltage mode)
Napetostni signal je integral naboja.
Velik in dolg signal.
$t_r = \tau_s$, $t_d = RC$, $U_{max} = Q/C$

Če RC<< τ_s (current mode)
Napetostni signal sledi scintilatorju.
Kratek in majhen signal.
$t_r = RC$, $t_d = \tau_s$, $U_{max} = (Q/C)(RC/\tau_s)$

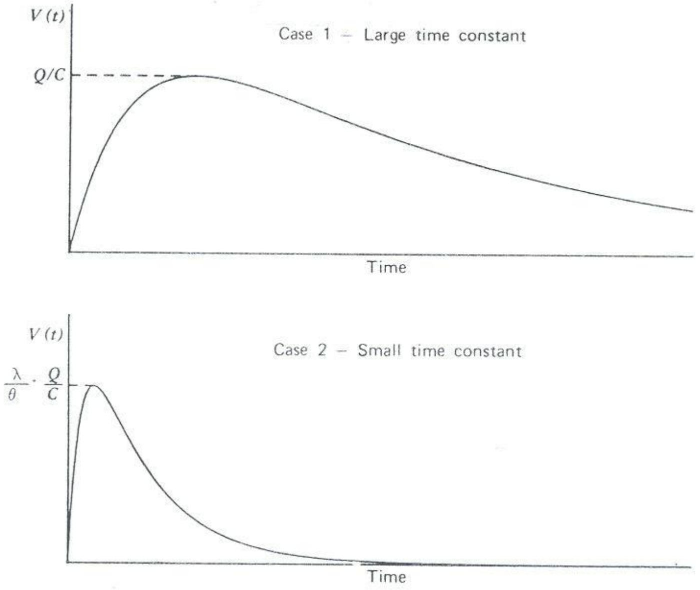


Figure 9-17 For the assumed exponential light pulse shown at the top, plots are given of the anode pulse $V(t)$ for the two extremes of large and small anode time constant. The duration of the pulse is shorter for Case 2, but the maximum amplitude is much smaller.

Časovna ločljivost

- Če za dogodek (absorpcija delca v scintilatorju) dobimo le en fotoelektron, bo časovna ločljivost določena s τ_s .

- Poleg τ_s vplivajo na časovno ločljivost še:
  1) razlike v času potovanja fotonov do fotokatode in
  2) razlike časov potovanja fotoelektronov od katode do prve dinode (geometrijske razlike poti in razlike začetnih hitrosti, $\Delta t \approx 0.2\text{-}0.5$ ns)

Za dobro časovno ločljivost želimo:

- hiter scintilator (majhen τ_s)
- velik pridelek
- dobro fotopomnoževalko (velik QE in hitra FP)

Zunanji vplivi

1) Osvetlitev fotopomnoževalke
   - pod napetostjo uniči FP ali v najboljšem primeru poveča temni tok
   - osvetlitev brez napetosti poveča šum, ki pa se s časom zmanjša

2) Magnetno polje (slike)
   - spremeni elektronske kaskade in zmanjša velikost signala
   - najbolj občutljiv del je zbiralni sistem of fotokatode do prve dinode
   - zaščita z μ-metalom in mehkim Fe
   - nove FP z “proximity focusing” so manj občutljive na B

3) Temperatura
   - poveča termični šum
   - QE je lahko odvisen od T (-0.5 %/^{0}C)

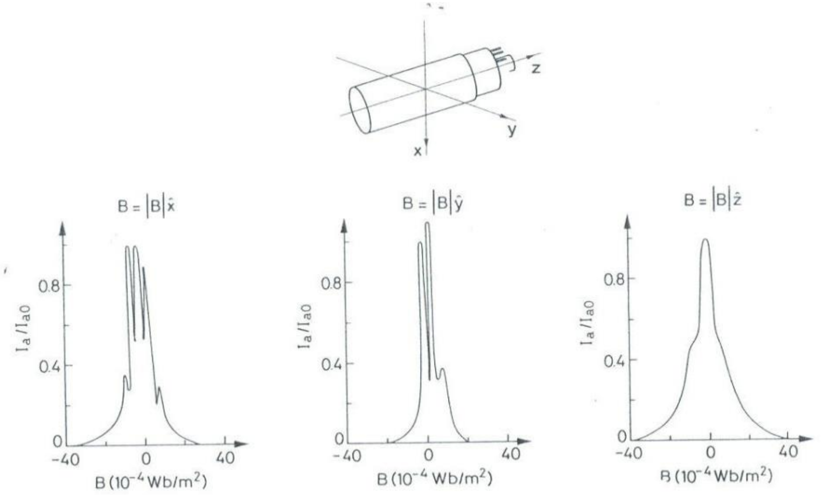


Fig. 8.17. Effect of magnetic fields on the anode current of an unscreened PM for different field orientations (from *Schonkeren* [8.1])

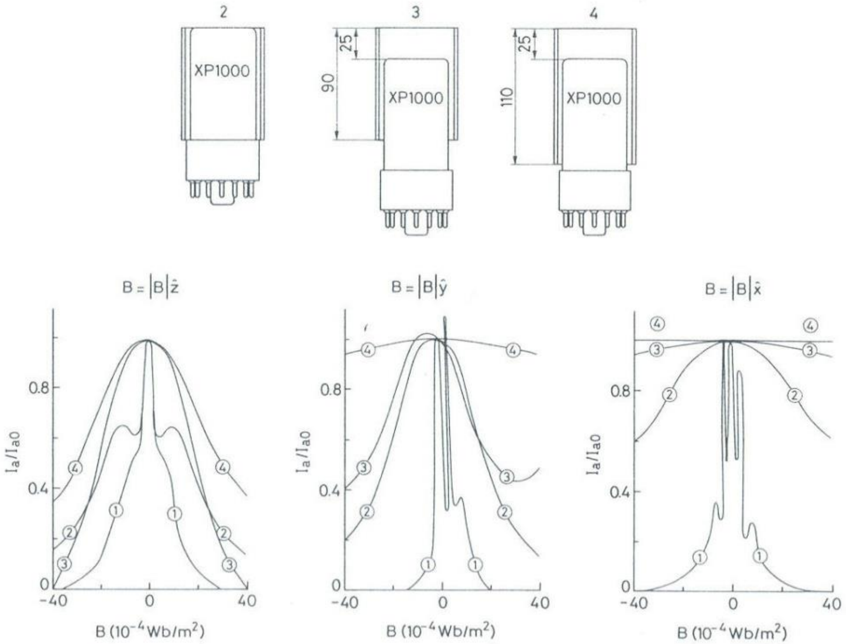


Fig. 8.18. Shielding effect of different mu-metal configurations (from *Schonkeren* [8.1])

2) Večanodne fotopomnoževalke in mikrokanalne plošče

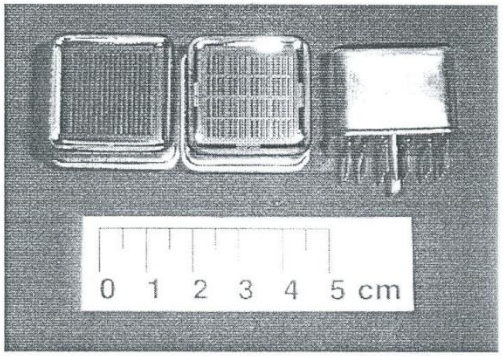
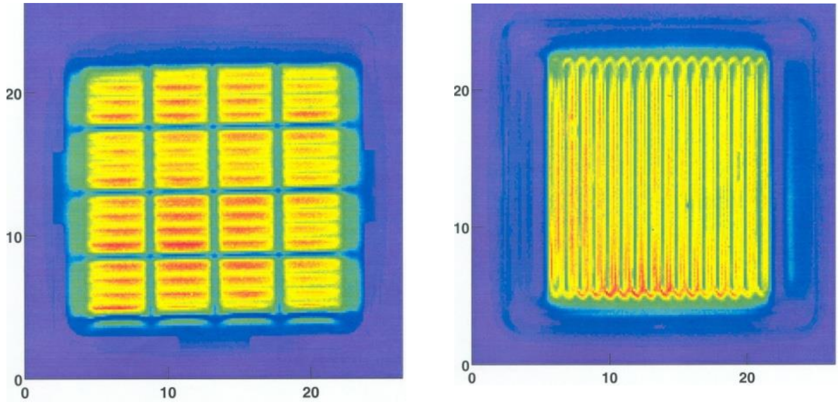
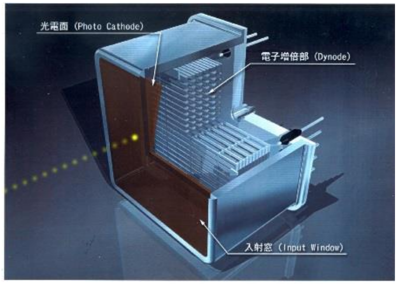


FIGURE 2. Hamamatsu multianode photomultipliers (L16, M16, M16 from left to right).





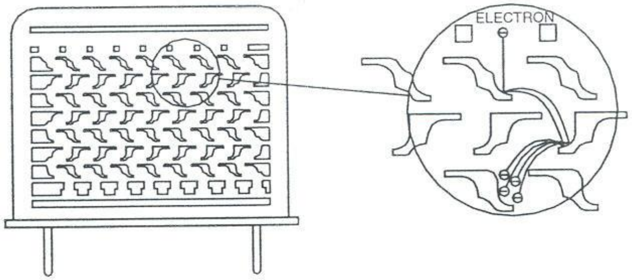
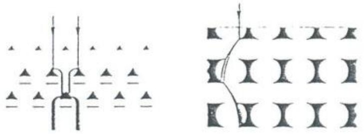


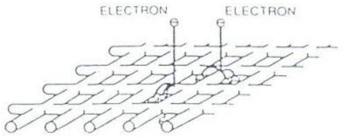
FIGURE 4. Metal channel type PMT [8].

POSITION SENSITIVE PMT'S - EXAMPLES

Philips mesh
and foil types



Hamamatsu
fine mesh

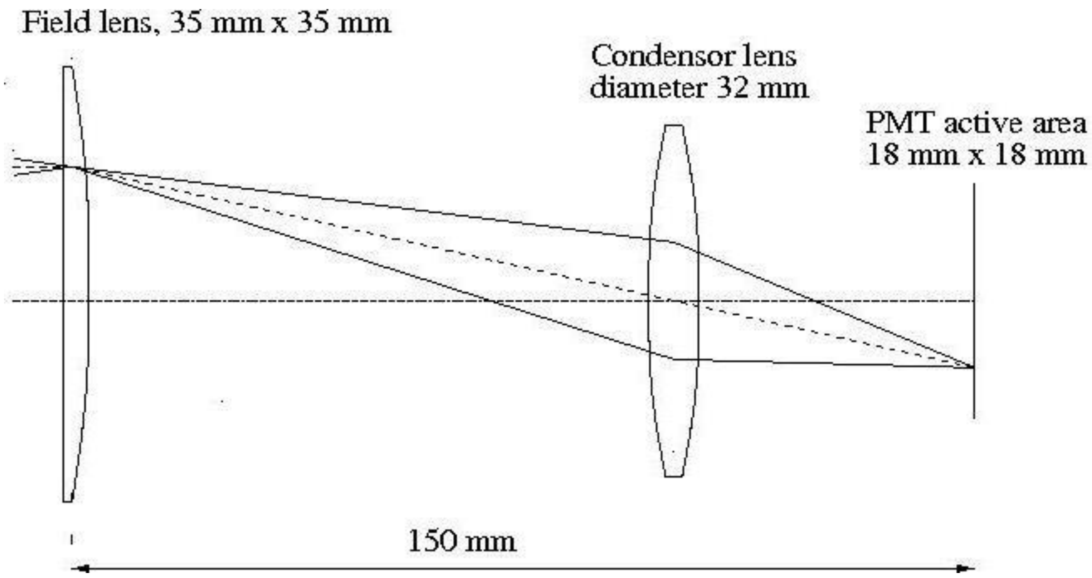


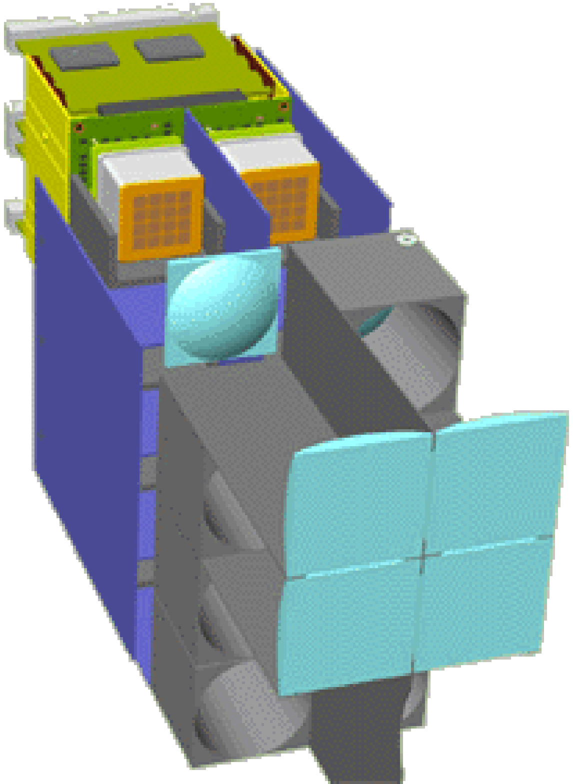
Light collection for a multianode PMT

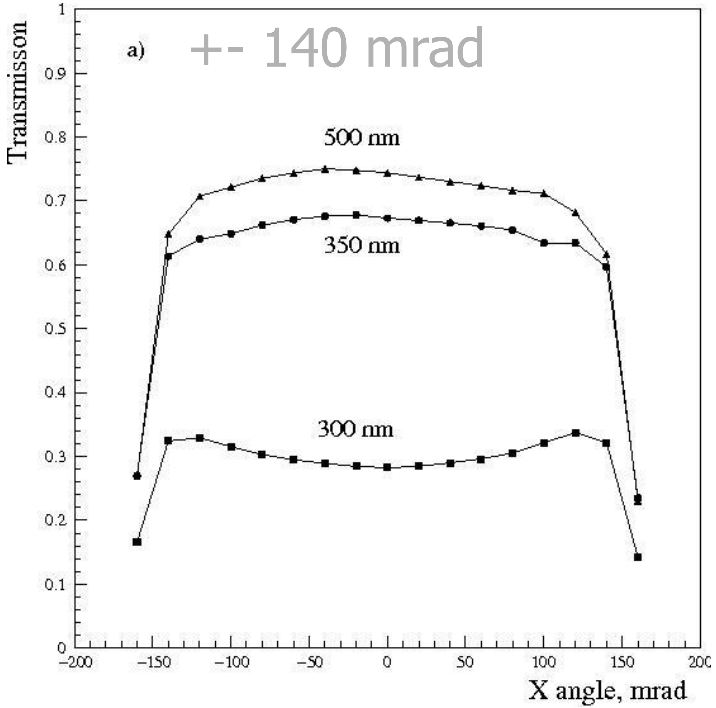
Light collection system (imaging!) to:

-Eliminate dead areas

-Adapt the pad size







+- 140 mrad

Mikrokanalne plošče

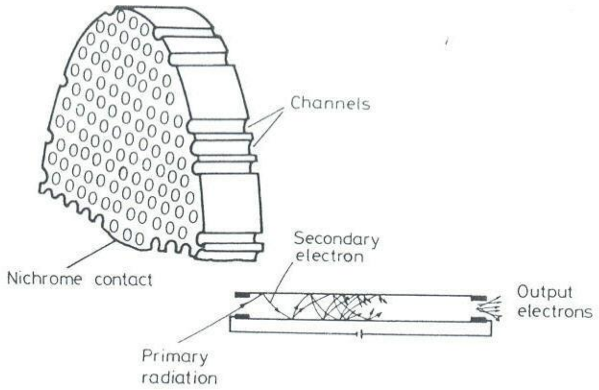


Fig. 8.6. Schematic diagram of a microchannel plate. The many channels act as continuous dynodes (from *Dhawan* [8.4]; picture © 1975 IEEE)

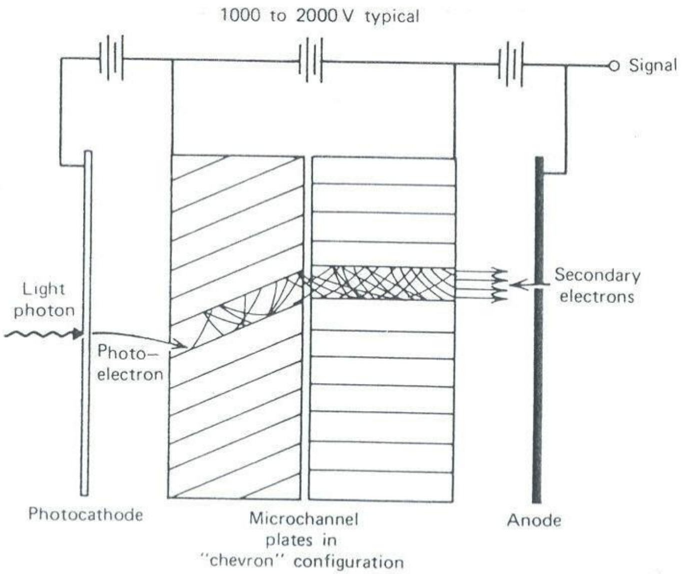


Figure 9-9 Elements of a PM tube based on microchannel plate electron multiplication.

- premer kanala 10-100 μm
- dolžina kanala $\approx$ 1mm
- površina plošče 10-50 cm^2
- ojačenje G $\approx 10^5$-10^7 ("chevron")
- časovna ločljivost <100 ps
- pozicijska občutljivost
- kanal 25 μm: do B$\approx$0.8T
- kanal 10 μm: do B$\approx$1.5T

3) Polprevodniški senzorji

Fotodiode (PD)

- velik kvantni izkoristek (tudi v IR področju),
- ni ojačanja
- uporabno v primerih, ko je veliko svetlobe (recimo v fiziki delcev za kalorimetrijo)

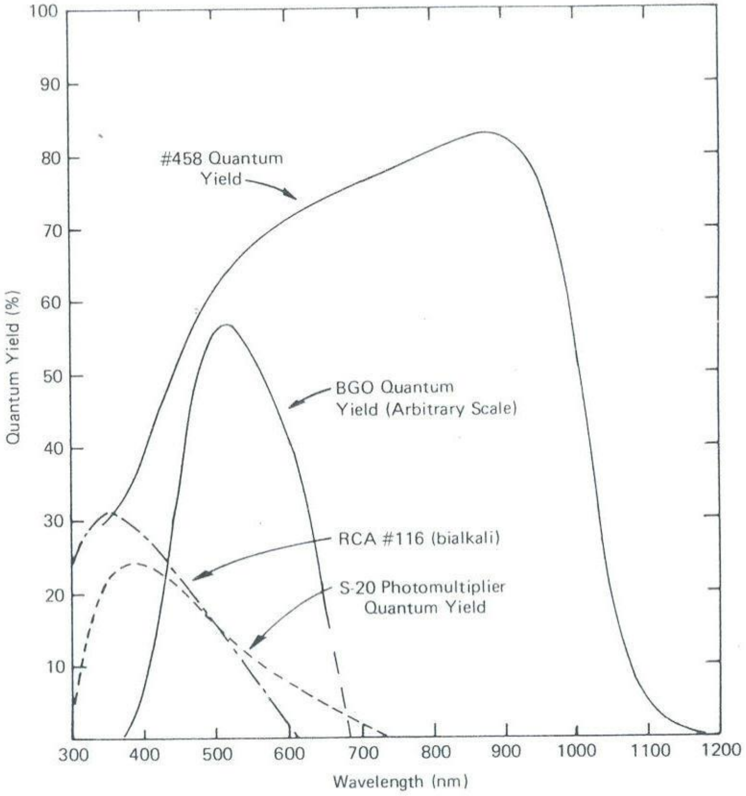
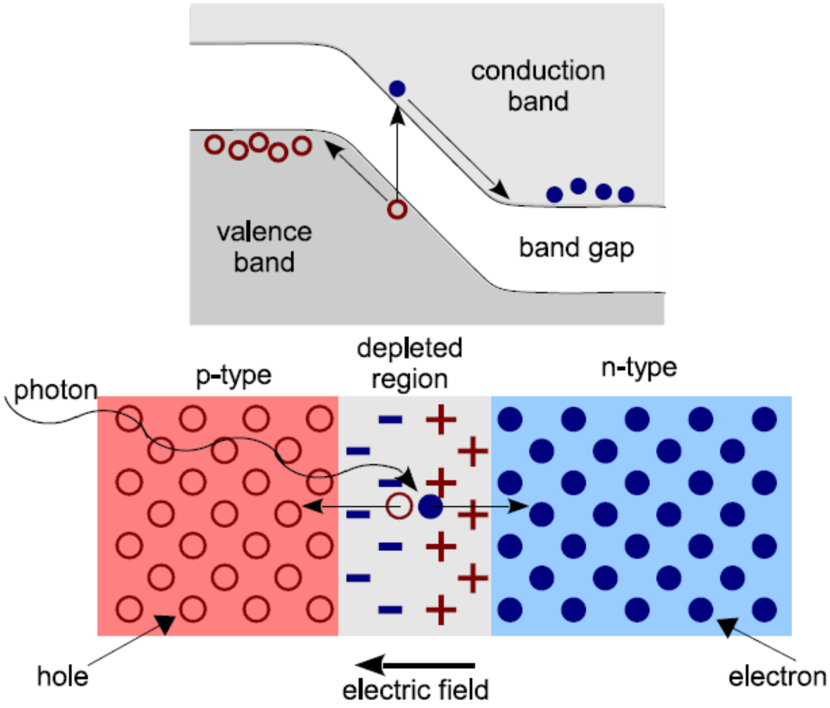


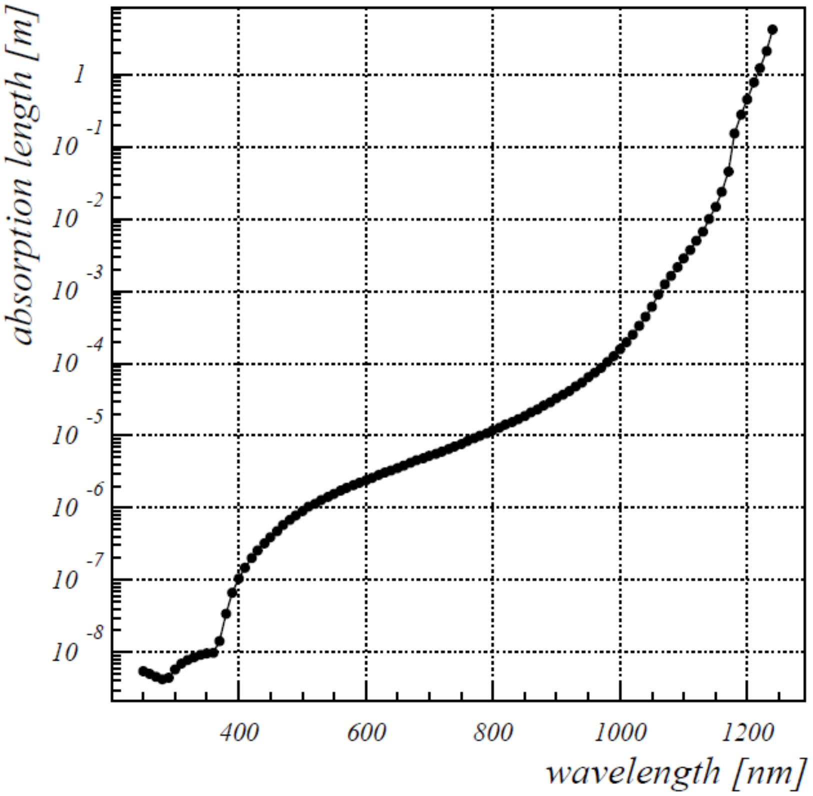
Figure 9-14 A comparison of the quantum efficiency of a silicon photodiode (labeled #458) with representative bialkali and S-20 photocathode quantum efficiencies. The emission spectrum from a BGO scintillator is shown for reference. (From Groom.[53])

Plazovne fotodiode (avalanche photodiodes, APD)

- veliko E povzroči pomnoževanje v plazu, G ≈ 10^2-10^3.
- razmerje šum/signal je več redov velikosti slabše kot pri FP,
- šum ≈0.4 nA/mm^2
- uporaba v fiziki delcev za kalorimetrijo

Semiconductor light sensor: photodiode





Semiconductor light sensor: CCD

Semiconductor light sensor: G-APD

G-APD: Geiger mode avalanche photo-diode, also known as SiPM – Silicon Photomultiplier

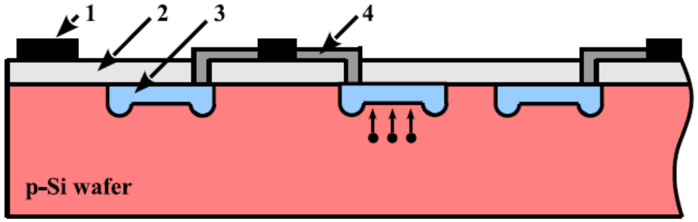


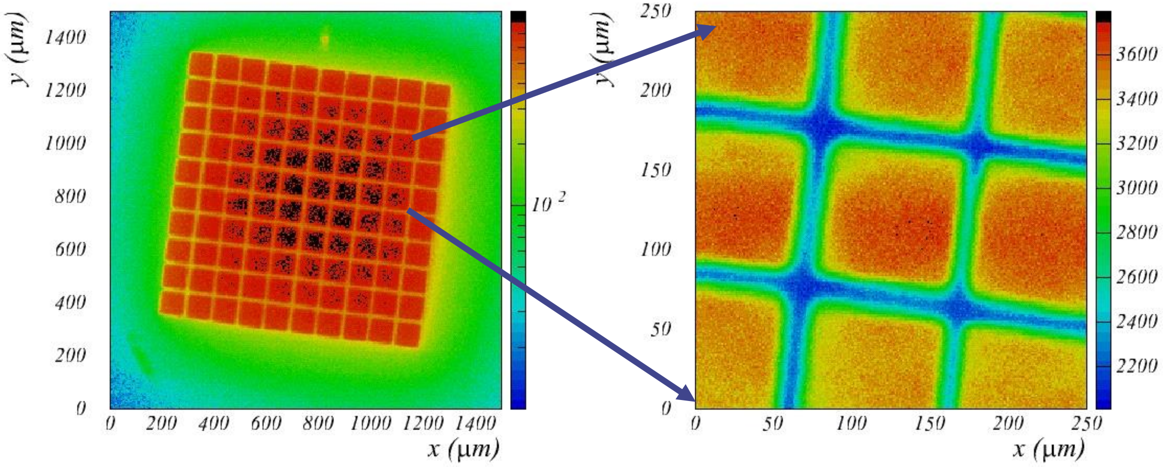
Figure 9: Schematic drawing of a cross-section of a SiPM: metal electrode (1), silicon oxide layer (2), p-n junctions/micro-cell (3) and individual quenching resistor (4) (23).

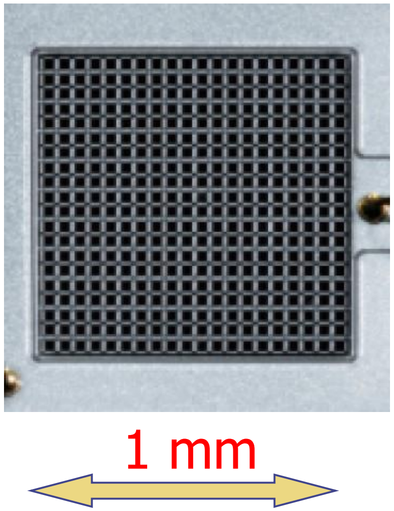
SiPM is an array of APDs operating in Geiger mode. Characteristics:

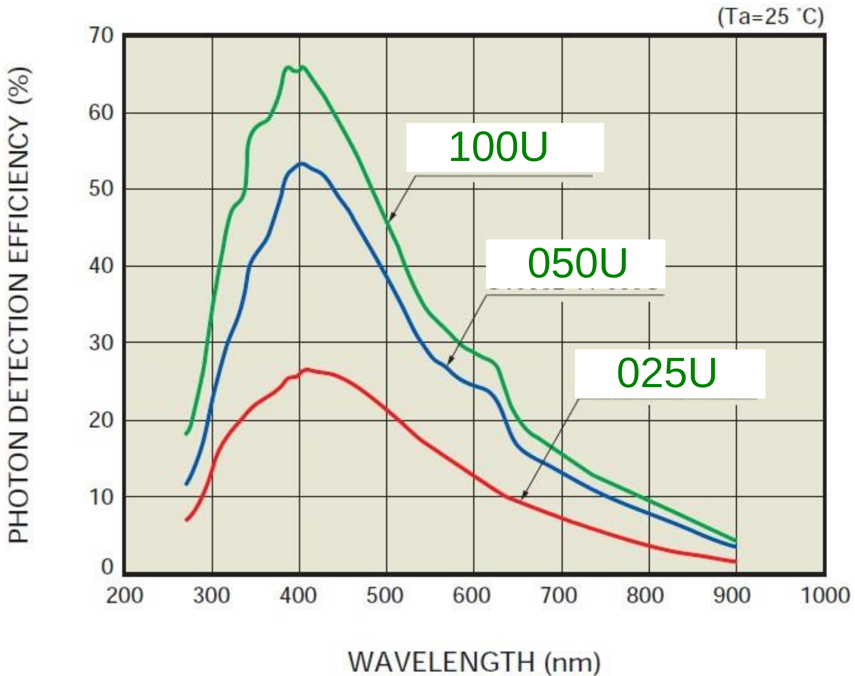
- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)

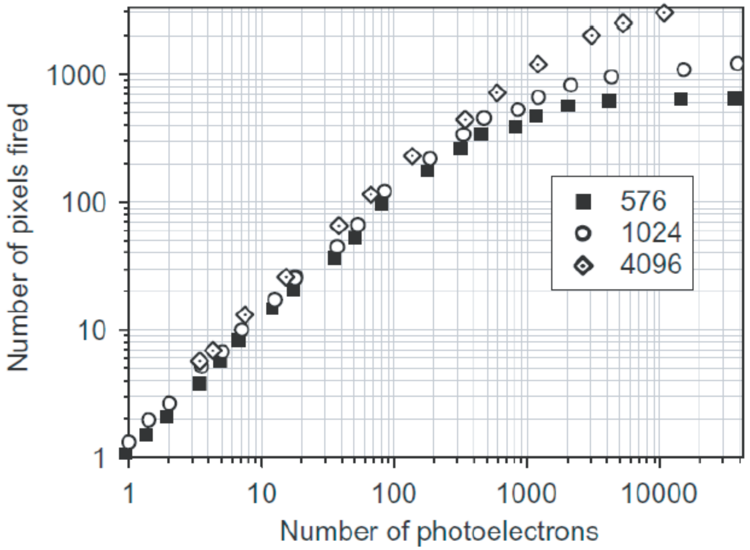
  PDE = QE x ε_{geiger} x ε_{geo} (up to 5x PMT!)
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- works in high magnetic field
- dark counts ~ few 100 kHz/mm^2
- radiation damage (p,n)

SiPMs as photon detectors



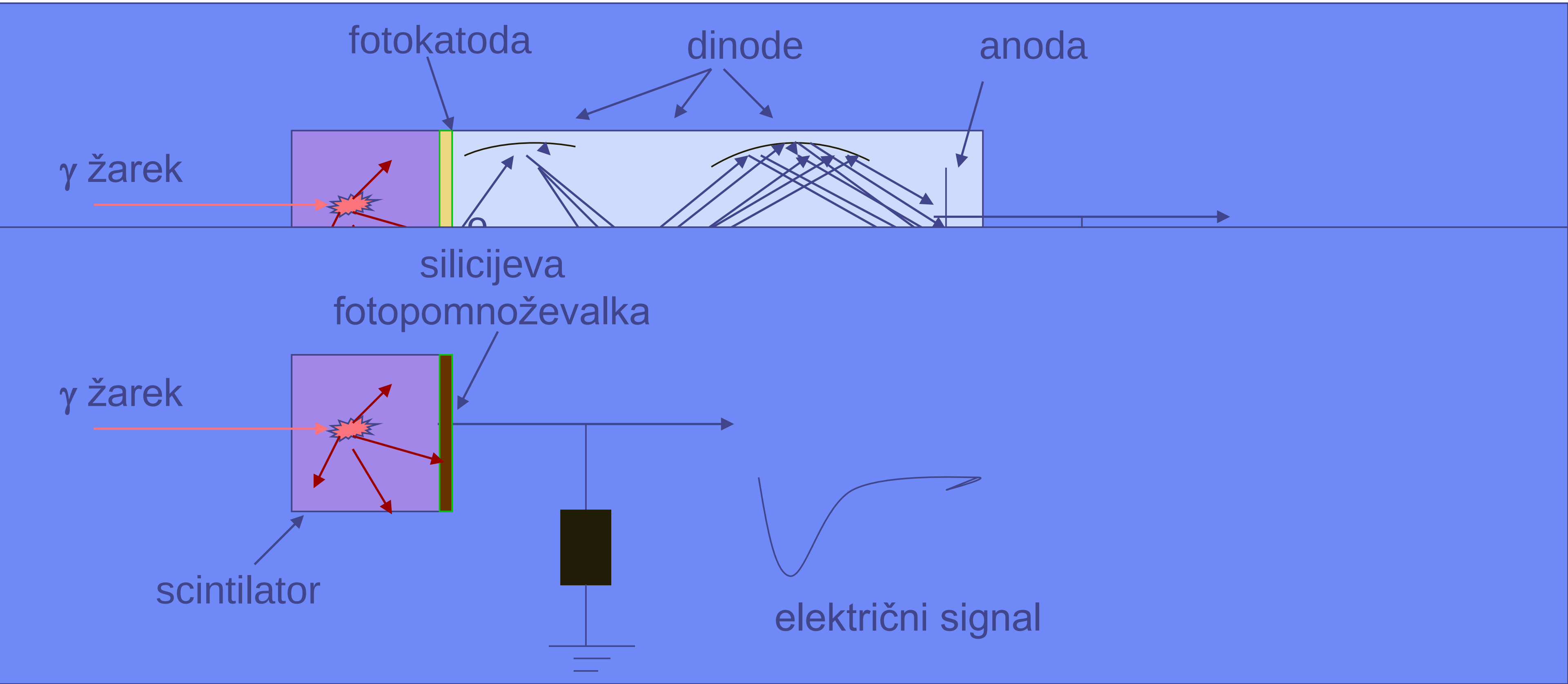


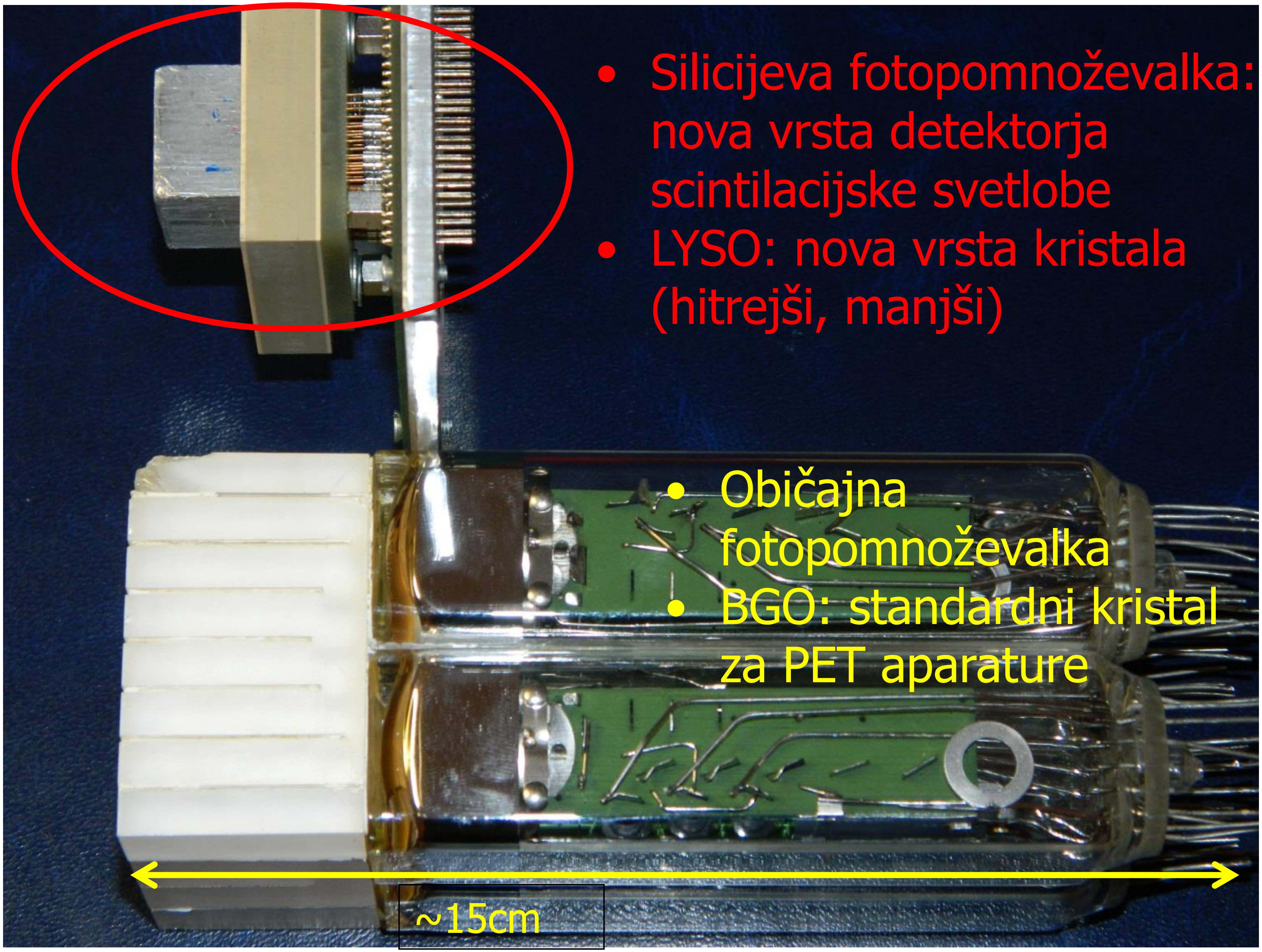




PET z novo vrsto senzorja

Silicijeva fotopomnoževalka: nova vrsta detektorja scintilacijski svetlobe, ki smo ga razvili za meritve v fiziki osnovnih delcev: → bistveno manjša od obstoječih detektorjev, ne potrebuje visoke napetosti, deluje v velikih magnetnih poljih (nekaj T).

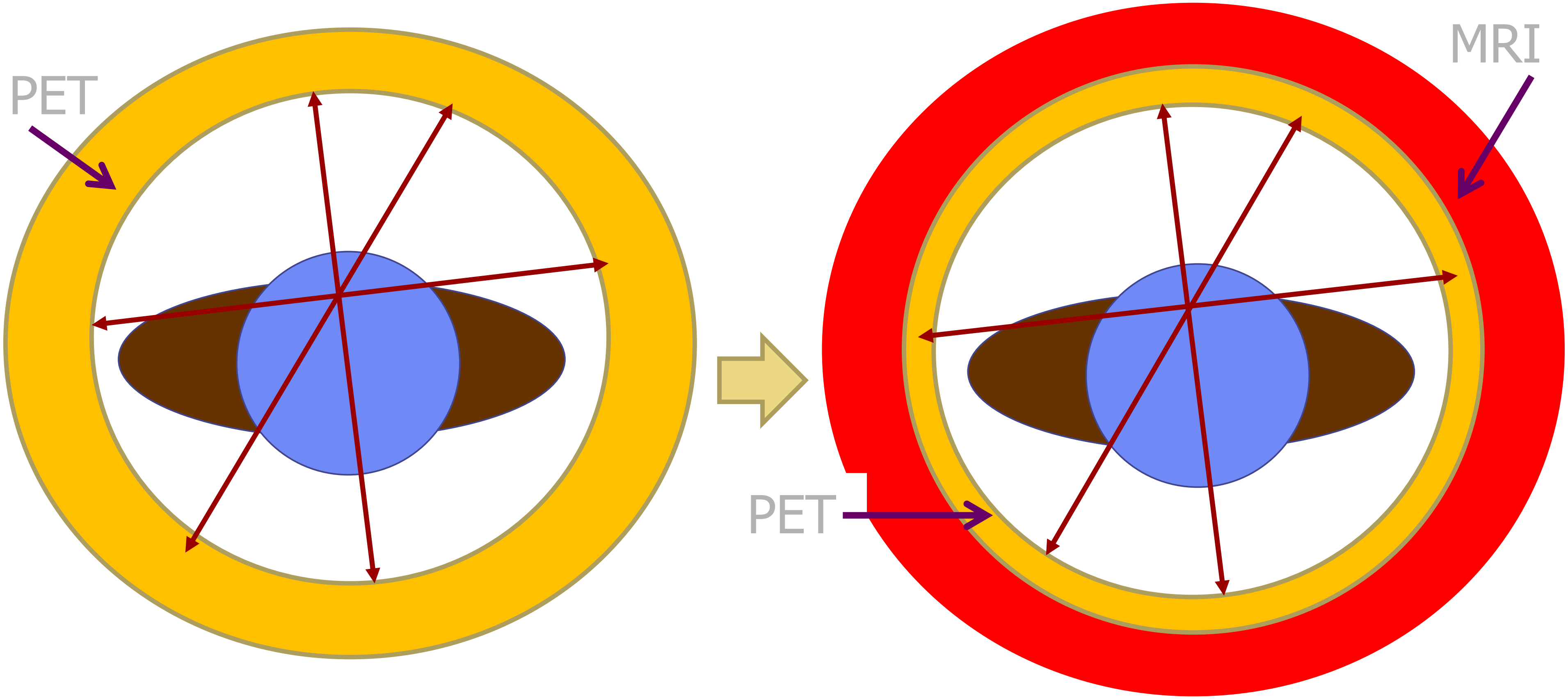




- Silicijeva fotopomnoževalka: nova vrsta detektorja scintilacijske svetlobe
- LYSO: nova vrsta kristala (hitrejši, manjši)

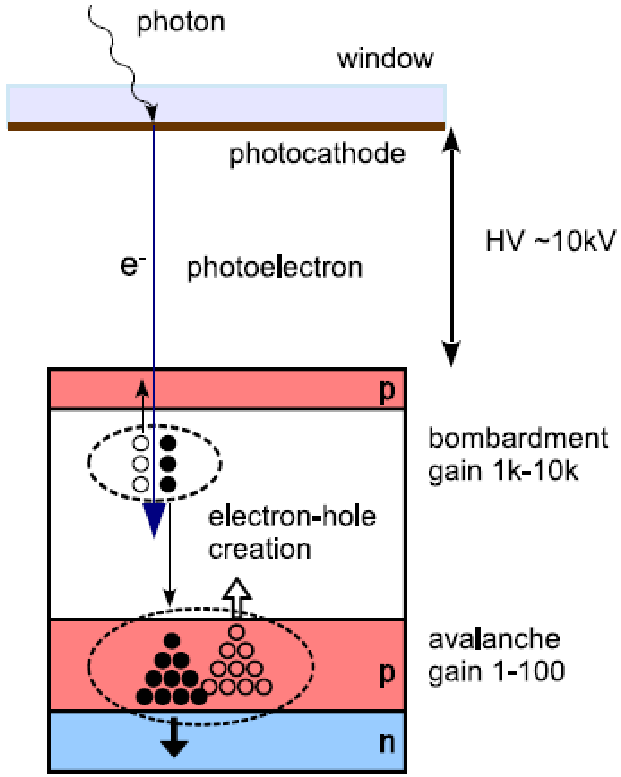
- Običajna fotopomnoževalka
- BGO: standardni kristal za PET aparature

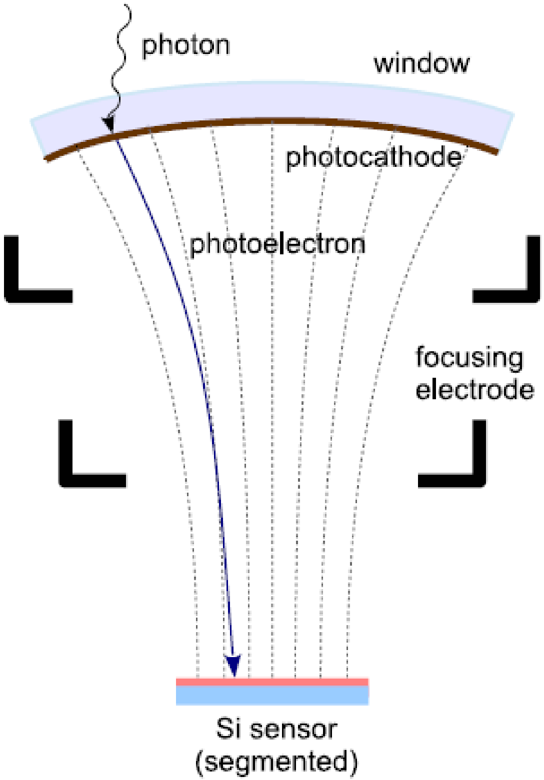
Nova vrsta senzorja, ki smo ga razvili za meritve v fiziki osnovnih delcev: → bistveno manjši od obstoječih detektorjev in deluje v velikih magnetnih poljih.



Omogoča sočasno slikanje z magnetno resonanco **in** PET – pomembna izboljšava za učinkovito diagnostiko!

Hybrid photo-detector HPD





4) Plinski detektorji svetlobe

=VŽPK + (TMAE, TEA ali CsI)

- plinu v VŽPK dodamo paro z nizkim ionizacijskim potencialom

-TEA ; E_{ion} =7.5 eV, p_n =5 tor, $\lambda\approx$ 0.6 mm pri 20^0C
-TMAE; E_{ion}=5.4 eV, p_n==0.35tor, $\lambda\approx$ 23 mm pri 20^0C

- izbiti elektron pomnožimo v plazu ob anodni žici VŽPK
- krajevna občutljivost

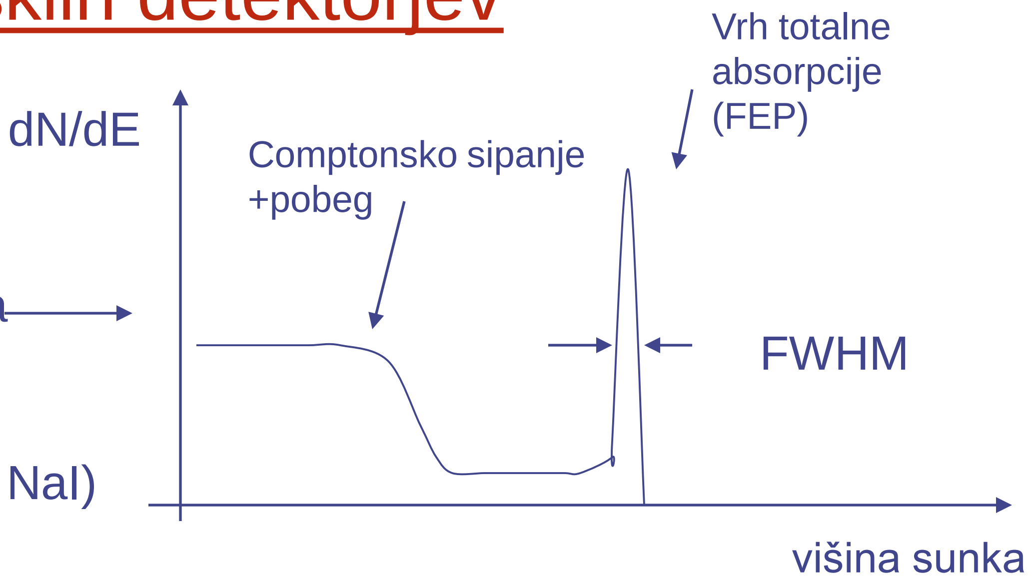
- CsI
  - naparimo ≈500 nm na katodo
  - QE podobno kot pri TMAE
  - ni paralakse
  - krajevna občutljivost
  - vprašljiva obstojnost

III) Uporaba scintilacijskiih detektorjev

NIZKE ENERGIJE

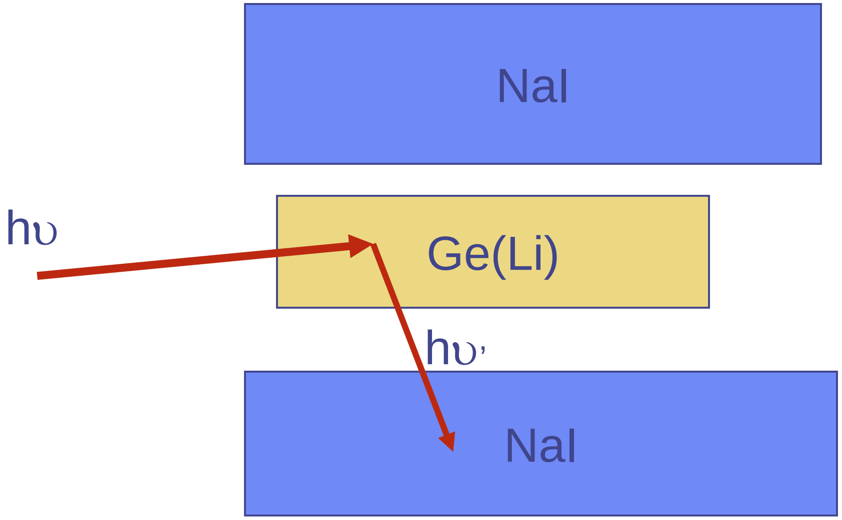
a) žarki gama

spekter monokromatskih gama →



Fotoefekt ∝ Z^5 , Compton ∝ Z
⇒scintilator naj ima velik Z (npr. NaI)

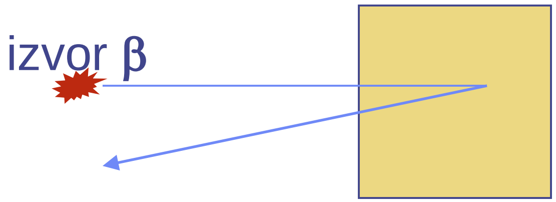
anti-Comptonski ščit:



Uporaba: medicina, varstvo okolja,
Geologija, industrija etc.

b)elektroni

-povratno sipanje (manjši Z ⇒ manj povratnega sipanja)



70-80% pri NaI

≈8 % pri plastiku

c) težki ioni

- za organske scintilatorje je velik “quenching” $L_\alpha = L_e/10$
- anorganski scintilatorji so boljši za ione $L_\alpha = 0.7\text{-}0.8\ L_e$

d) nevtroni

- hitri n: (n,p) reakcije v organskem scintilatorju, ki vsebuje vodik
- diskriminacija z obliko sunka

- termični n: scintilator naj vsebuje ^{6}Li ali ^{10}B (velik presek za zajetje)

  LiI(Eu), d=2cm, izkoristek 90% za termične nevtrone,
  stekla, ki vsebujejo Li ali B,
  tekoči scintilatorji.

VISOKE ENERGIJE

- za prožilne signale (triger ali veto)
- za meritev časa preleta (Time-Of-Flight, TOF)
- za meritev celotne energije (kalorimetrija)
- za meritev Čerenkovih obročev (RICH)