BENASQUE II

MONTE CARLO, RESLUTION, PHOTN DETECTORS ETC

THE CALIBRATION PROBLEM

- ANY USEFUL DETECTOR NEEDS TO BE CALIBRATED, AT LEAST BEFORE STARTING NORMALLY FREQUENTLY CROSS-CHECKED IN ORDER TO CONVERT ANY OBSERVED QUANTITY INTO THE CORRECT PHYSICS UNITS.
  EXAMPLE: CONVERSION OF A LIGHT SIGNAL FROM A FLUORESCENT DETECTOR INTO THE INITIAL PARTICLE ENERGY IN eV.

A) ONE CAN SOMETIMES DO OVERALL CALIBRATIONS
EXAMPLE IN HEP: CALIBRATION OF A CALORIMENTER IN A TEST BEAM
ELECTRON BEAM, PROTON BEAM OF DIFFERENT ENERGY

B) WHEN NO TESTBEAM AVAILABLE: CALIBRATION OF ALL COMPONENTS AND CALCULATION OF THE RESPONSE
EXAMPLE: THE OPTICAL PERFORMANCE OF A CHERENKOV TELESCOPE
RAY TRACING, $R(\lambda)$,$QE(\lambda)$, SIGNAL TRANSMISSION IN PMT

IN HIGH ENERGY ASTROPARTICLE PHYSICS: NORMALLY NO TEST BEAM AVAILABLE (DIFFERENT: IN LOW ENERGY ASTROPARTICLE PHYSICS DETECTORS ONE CAN USE ACCCELERATOR TEST BEAMS: EXAMPLE CALIBRATION OF THE GLAST DETECTOR WITH ELECTRON (ψ) TESTBEAM)

THE **MONTE CARLO** METHOD ALLOWS YOU TO CREATE A ‘SOFTWARE TEST BEAM’

NEEDS NORMALLY THE INPUT FROM THE PHYSICS PROCESS TO BE STUDIED
AND PERFORMANCE INPUT FROM ALL COMPONENTS
OFTEN ALSO THE UNWANTED BACKGROUND PROCESSES MUST BE ADDED

MONTE CARLO (MC) SIMULATIONS ARE VERY IMPORTANT FOR COMPLEX PROCESSES OR WHEN STOCHASTIC PROCESSES ARE INVOLVED AND ANALYTICAL OR SEMIANALYTICAL CALCULATIONS ARE IMPOSSIBLE
EXAMPLE OF AN STOCHASTIC PROCESS: SHOWER DEVELOPMENT IN AN ABSORBER
DECAY PROCESSES, INTERACTION OF HIGH ENERGY PARTICLE

ADVANTAGES OF THE MC METHOD
- ALLOWS DETRECTOR OPTIMISATION BY TESTING MANY DETECTOR VARIANT
- COST OPTIMISATION
- REPLACES OFTEN HARDWARE TESTS
- EXAMPLE: DESIGN OF A WING OF AN NEW AIRPLANE
  CRASH RESPONSE OF A CAR

THE MC METHOD IS MUCH FASTER, ALLOWS MORE FLEXIBILITY AND IS BECOMING CHEAPER DUE TO INCREASING COMPUTING POWER
YOU CAN BUILD A VIRTUAL DETECTOR AND TEST IT ON YOUR PC !!!

WHERE ARE THE PROBLEMS
IT’S A VITUAL, NOT A REAL TEST ‘BEAM’
YOU CAN EASILY MAKE A MISTAKE

IF ONE FORGETS SOMETHING VITAL OR DOES NOT KNOW IT--> WRONG RESULT

MOST COMMON: PROGRAMMING ERRORS

SIMPLIFICATIONS, OFTEN NEEDED BECAUSE OF LIMITED COMPUTER POWER
EXAMPLE: PHOTONS IN AN AIR SHOWER: ONE CANNOT TRACE ALL PHOTONS
EXAMPLE: BEAM BEAM INTERACTION IN STORAGE RINGS, 1010-1011 PARTICLES PER BUNCH MOVING WITH c

WHEN DOING SIMPLIFICATIONS : BE AWARE THAT CORRELATIONS ARE NOT LOST

UNKNOWN BACKGROUND CONTRIBUTION (THER ARE VERY FEW EYAMPLES OF BACKGROUNFFREE DETERCTORS. NOISE, EXTERNAL BACKGROUND)

→SOME TESTS ARE LATER UNAVOIDABLE AND NECESSARY TO VERIFY AND TO CALIBRATE AT LEAST THE MAIN PERFORMANCE

HIGH ENERGY ASTROPARTICLE PHYSICS DETECTORS SUFFER MORE THAN MOST OTHER DETECTORS FROM THE LACK OF TEST BEAMS

EXAMPLE OF PROBLEMS: CROSS SECTION, DECAYS IN EE PROCESSES
ν MASSES, MIXING IN PROCESSES OBSERVED
OVER COSMOLOGICAL DISTANCES
CR BACKGROUND IN ‘CHERENKOVLIGHT’
FLUXES, PARAMETERS OF WIMPS

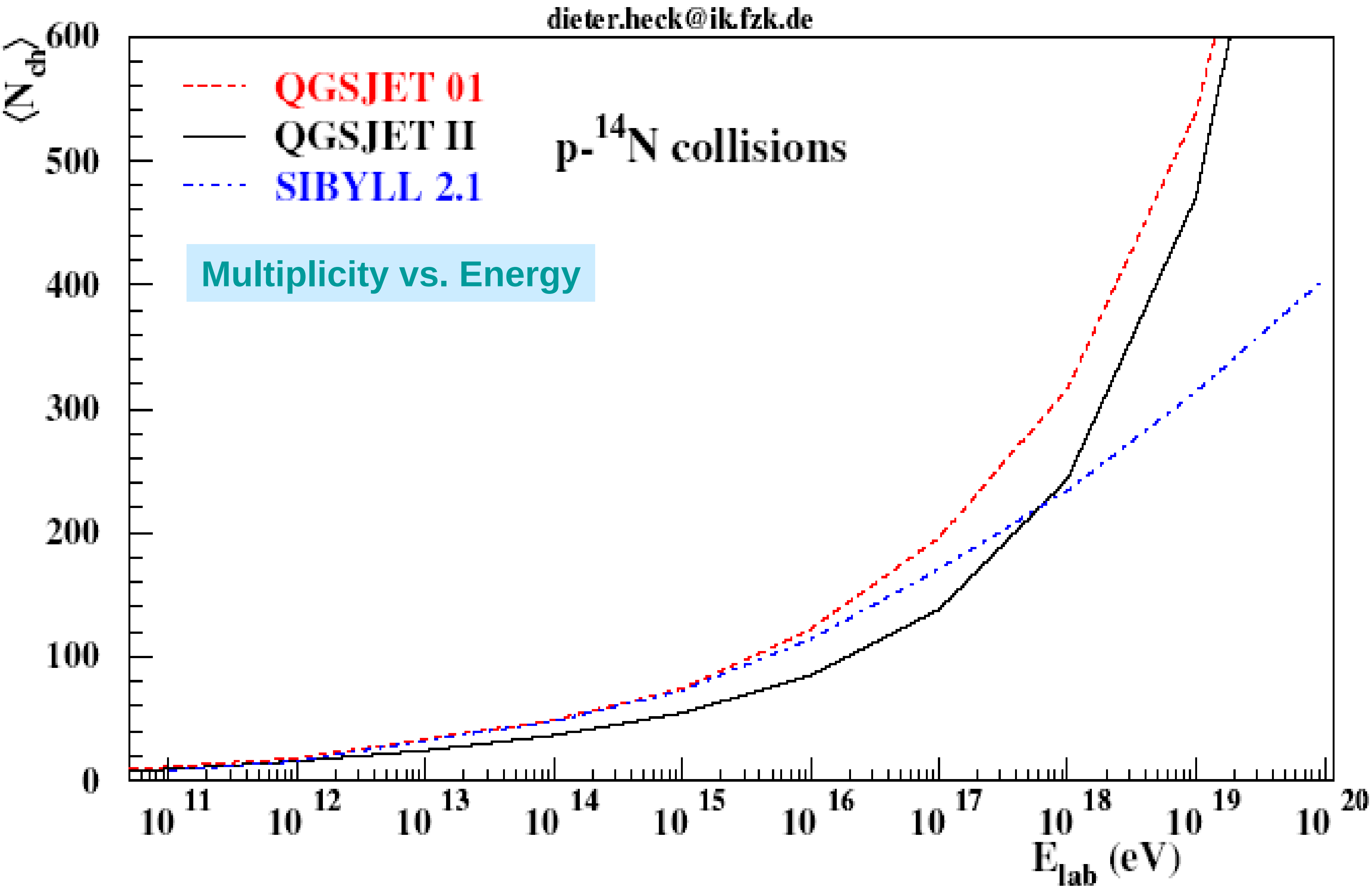
FOR HADRONS: INTERACTIONS NOT STUDIED WELL ABOVE
100 IN THE FOREWARD DIRECTION
NEED MODEL EXTRAPOLATIONS

RELY MORE ON MC ‘TEST BEAMS’

USE OF ‘STANDARD CANDLES’
A PROCESS WHICH IS EASY OBSERVABLE AND IS STABLE

EXAMPLE: GAMMA EMISSION FROM THE CRAB NEBULA IN VHE γ ASTRONOMY
(DOWN TO WHAT LEVEL STABLE OVER SHORT, OVER LONG TIMES?)
SUN FOR THE CALIBRATION OF HE ν DETECTROS

New hadronic model: QGSJETII Heck and Ostapchenko ICR 2005



Multiplicity vs. Energy

PHOTON DETECTORS: SOME GENERAL PARAMETERS

*SPECTRAL RANGE (λ): $\approx$ 200 nm TO $\approx$ 1.5 μ ;

-> visible spectrum + part of the UV and IR spectrum

-> limits not sharply defined

200nm : transmission cutoff of few mtr. of atmosphere

1.6 μ : practical upper limit of single photon detection

•QUANTUM EFFICIENCY: IMPORTANT NUMBER THAT DESCRIBES THE CONVERSION PROBABILITY OF A PHOTON (PHOTONS) INTO ELECTRONS

QE = #of photoelectrons /# of incident photons

QE is wavelength dependent : QE = QE (λ)
but the photoelectrons (PHE) do normally not carry info on the energy (color) of the photons!

QE is normally < 1
for internal photoeffect QE can reach nearly 1(example Si-PIN photodiode)
for external photoeffect: QE <1 (best PMTs ≈ 30%, best hybrid PMT ≈50%)

PHOTON DETECTORS: SOME GENERAL PARAMETERS

* CONVERSION TIME: CONVERSION PHOTON->PHOTOELECTRON IS PROMPT
ANY DELAY IS DETECTOR SPECIFIC
DELAY EXAMPLES: DIFFUSION OF A PHE IN MATERIAL
DELAY IN SIGNAL PROCESSING ELECTRONICS

* THE ENERGY OF A PHOTON IS TOO LOW (typ eV) TO BE DETECTED/PROCESSED BY NORMAL ELECTRONIC CIRCUITS

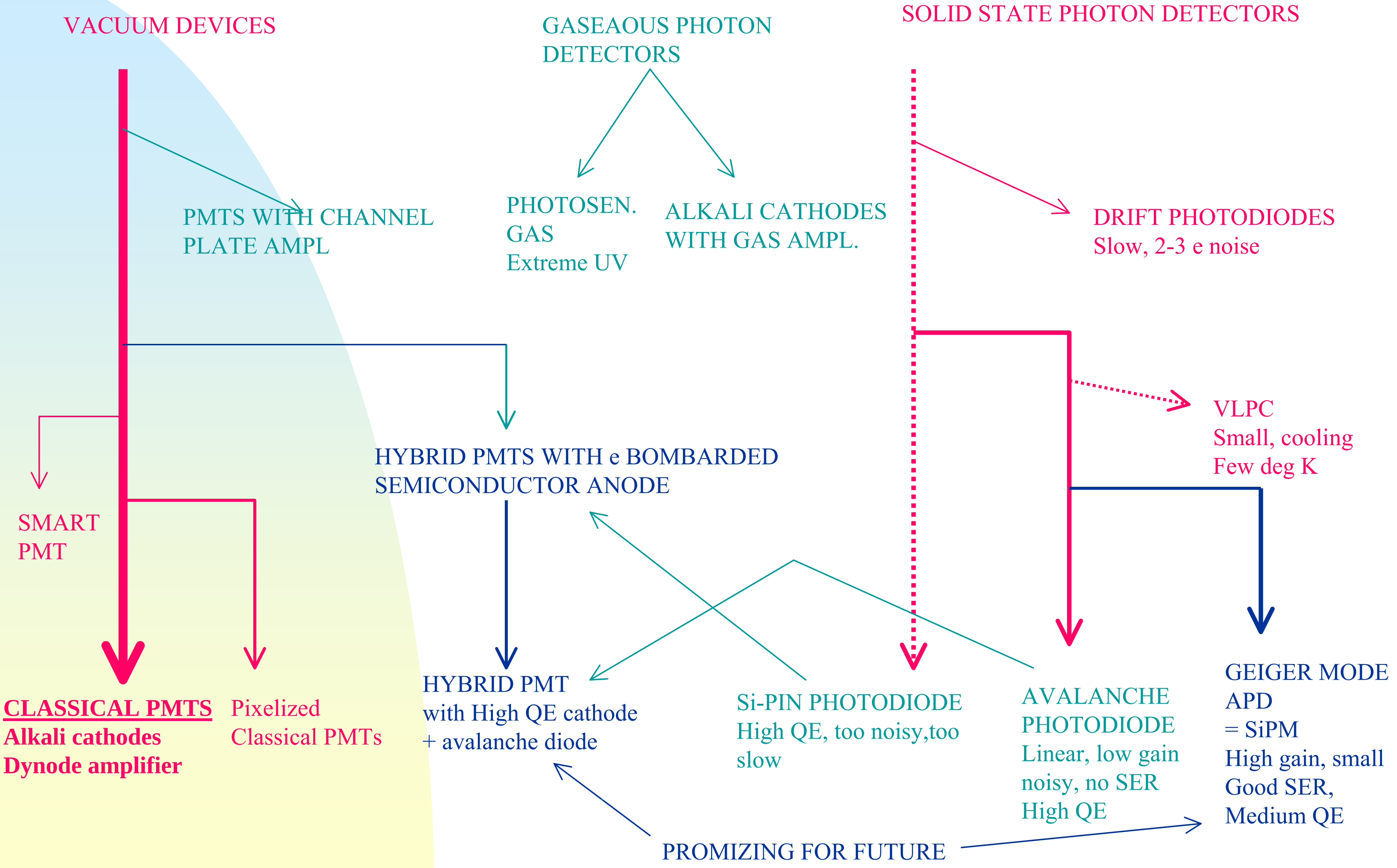
*-> NEEDS SPECIAL AMPLIFIERS
(NORMAL SEMICONDUCTOR AMPLIFIERS HAVE THE NEEDED BANDWIDTH BUT ARE MUCH TOO NOISY ,

*BEST WIDEBAND AMPLIFIERS (BW ≈ 500 MHZ) HAVE NOISE LEVELS OF EQ. FEW 1000 ELECTRONS AT INPUT
ADDITIONAL CONTRIBUTIONS FROM PARALLEL AND SERIAL NOISE

-> PHOTON DETECTORS NEED INTERNAL AMPLIFICATION IF ONE WANTS TO DETECT SINGLE PHOTONS

-> IN VACUUM PHOTON DETECTORS: ELECTRON MULTIPLICATION BY DYNODE SYSTEM
_> IN SOLID STATE DEVICES: AVALANCHE MULTIPLICATION IN SAME MATERIAL

FAMILIES OF PHOTON DETECTORS



VACUUM DEVICES

PMTS WITH CHANNEL
PLATE AMPL

SMART
PMT

CLASSICAL PMTS
Alkali cathodes
Dynode amplifier

Pixelized
Classical PMTs

HYBRID PMTS WITH e BOMBARDED
SEMICONDUCTOR ANODE

HYBRID PMT
with High QE cathode
+ avalanche diode

GASEAOUS PHOTON
DETECTORS

PHOTOSEN.
GAS
Extreme UV

ALKALI CATHODES
WITH GAS AMPL.

SOLID STATE PHOTON DETECTORS

DRIFT PHOTODIODES
Slow, 2-3 e noise

VLPC
Small, cooling
Few deg K

Si-PIN PHOTODIODE
High QE, too noisy,too
slow

AVALANCHE
PHOTODIODE
Linear, low gain
noisy, no SER
High QE

GEIGER MODE
APD
= SiPM
High gain, small
Good SER,
Medium QE

PROMIZING FOR FUTURE

THE CLASSICAL PHOTOMULTIPLIER

THE MAIN DEVICE TO DETECT SINGLE(FEW) PHOTONS
THE WORKHORSE OF NEARLY ALL DEVICES THAT RELY ON PHOTON DETECTION

COMBINATION OF CONVERTER OF PHOTONS TO ELECTRONS
AND HIGH GAIN AMPLIFIER(ELECTRON MULTIPLIER)

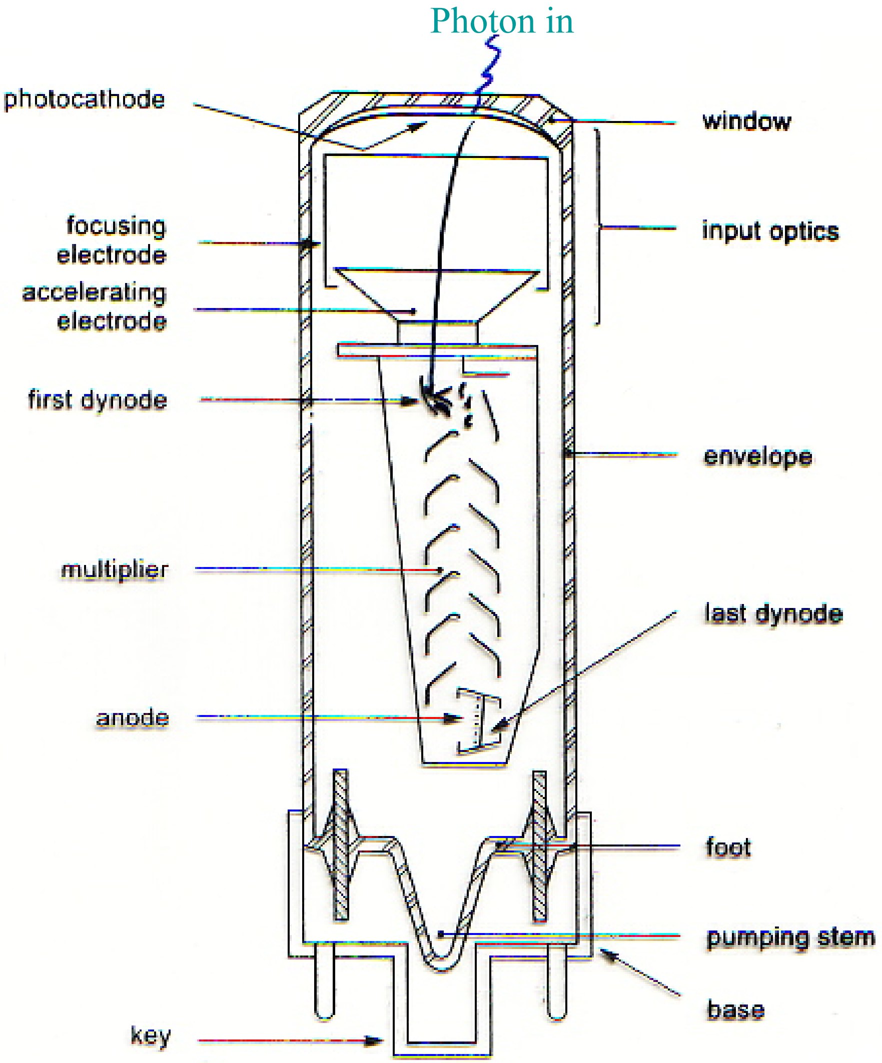
A SINGLE PHE HAS TOO LOW ENERGY TO BE PROCESSED->
NEEDS LARGE AMPLIFICATION

BASIC ELEMENTS:

- PHOTO CATHODE
- ELECTRON FOCUSSING ELEMENT TO FOCUS PHE ON SMALL AREA AMP. SYSTEM
- HIGH GAIN AMPLIFIER BY DYNODE SYSTEM
- ANODE TO COLLECT SIGNAL AND COUPLE TO DAQ SYSTEM

- AUXILIARY ELEMENTS: VACUUM CONTAINMENT, GLASS WINDOW, HT BIAS CIRCUITS
  MAGNETIC SHIELDING, MECHANICAL MOUNTING…

A TYPICAL PHOTOMULTIPLIER



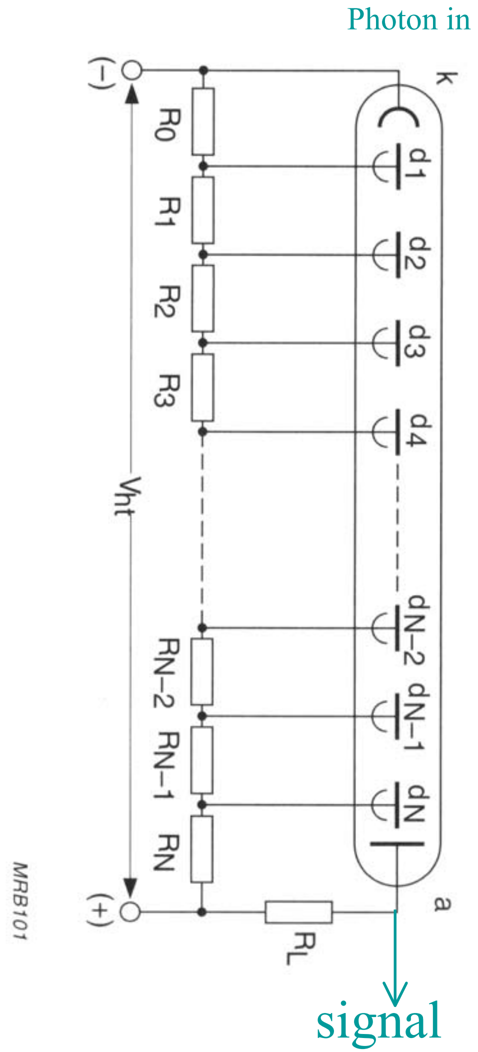


Fig.1.2 Voltage-divider high-tension supply

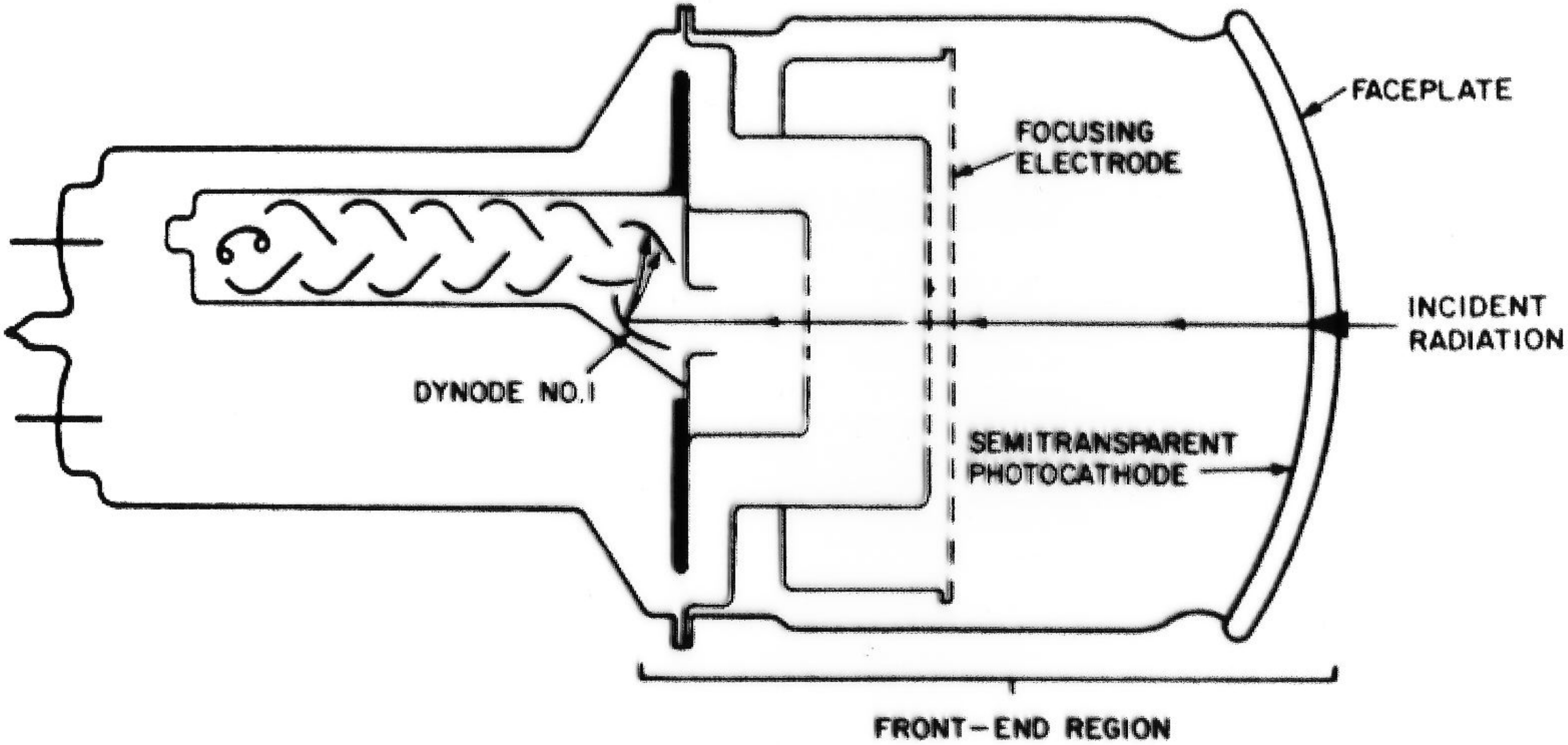
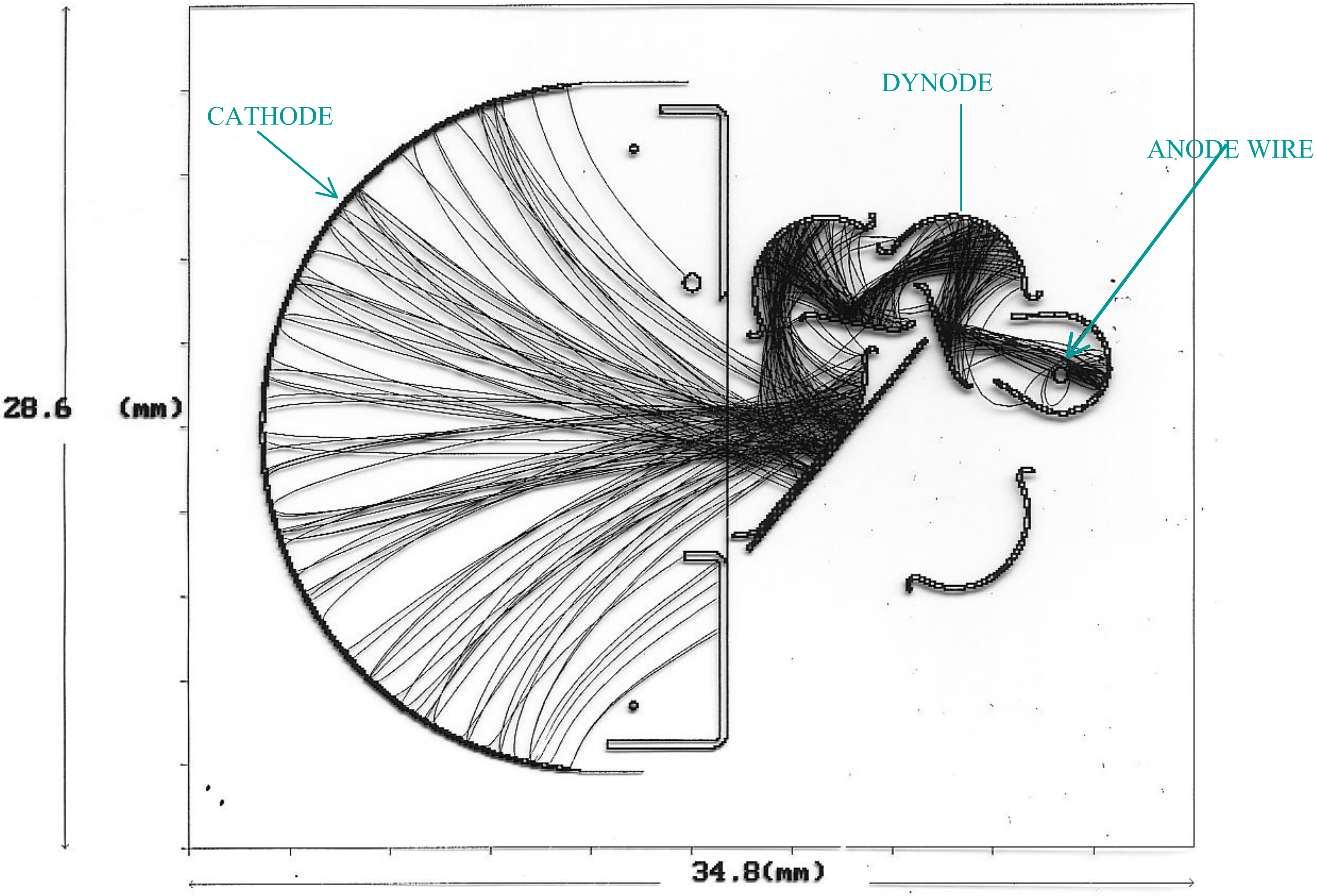


Abb. 6 Linear fokussierte Dynoden

EXAMPLE: PHOTOELECTRON TRACKS AND DYNODE MULTIPLICATION IN A PMT 9116



THE PHOTOCATHODE: BASICALLY A SEMICONDUCTOR WITH NEGATIVE ELECTRON AFFINITY

CESIUM COATING LOWERS EXIT WORK FUNCTION (part of phe do not get out of cathode -> recombine-->not 100% QE

CATHODES VERY THIN, FEW 10th Å -> SEMITRANSPARENT (partly reflecting, part of light not absorbed-lower QE)-

VACCUM PRODUCTION TECHNIQUE

CLASSICAL CATHODES: ALLOY: Sb NaKRb V-3(I) Semiconductor

STONE AGE EPITAXIAL GROWTH OF THE 50th

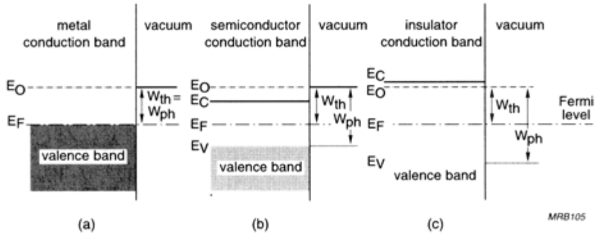


Fig.A1.4 Energy bands in (a) a metal, (b) a semiconductor, (c) an insulator

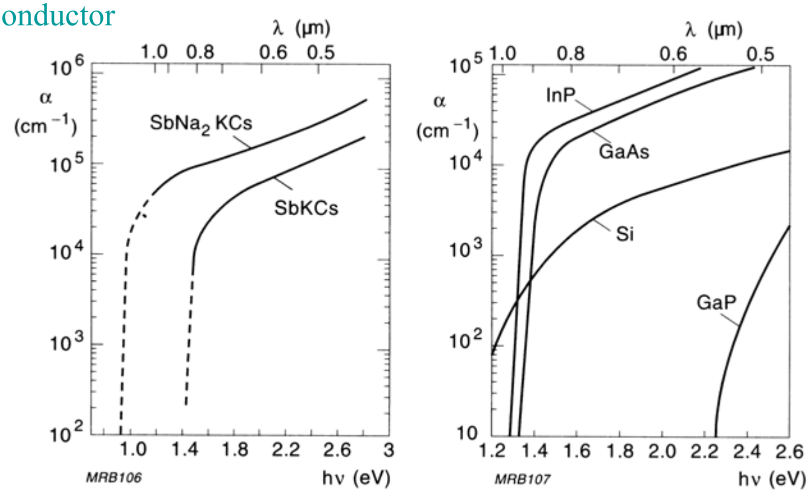


Fig.A1.5 Absorption coefficients α as functions of photon energy hν for various photoemissive layers

SPECTRAL RESPONSE AND GAIN CURVES

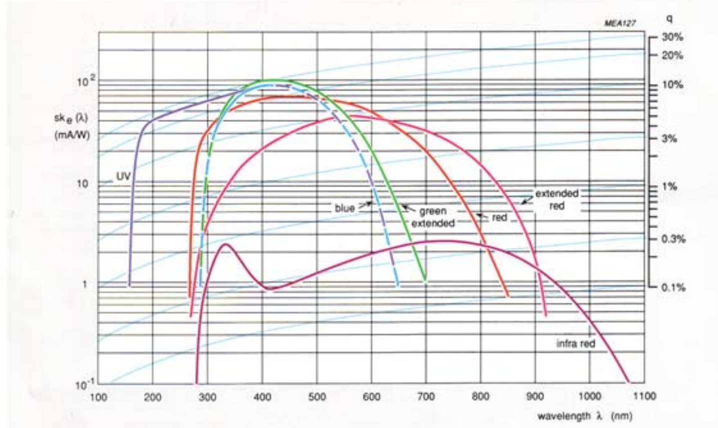
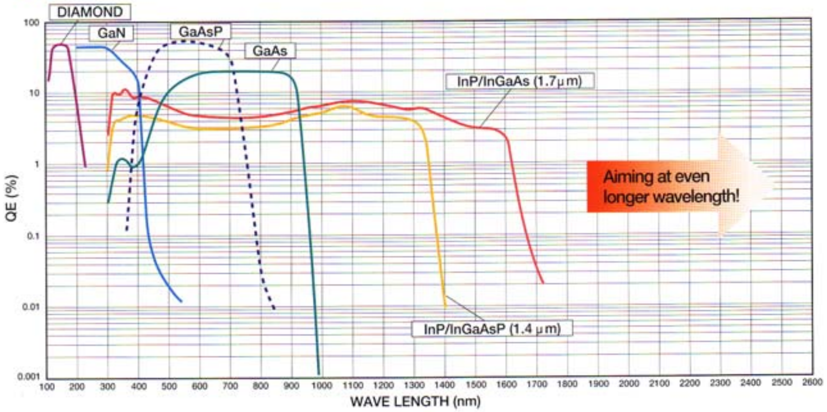
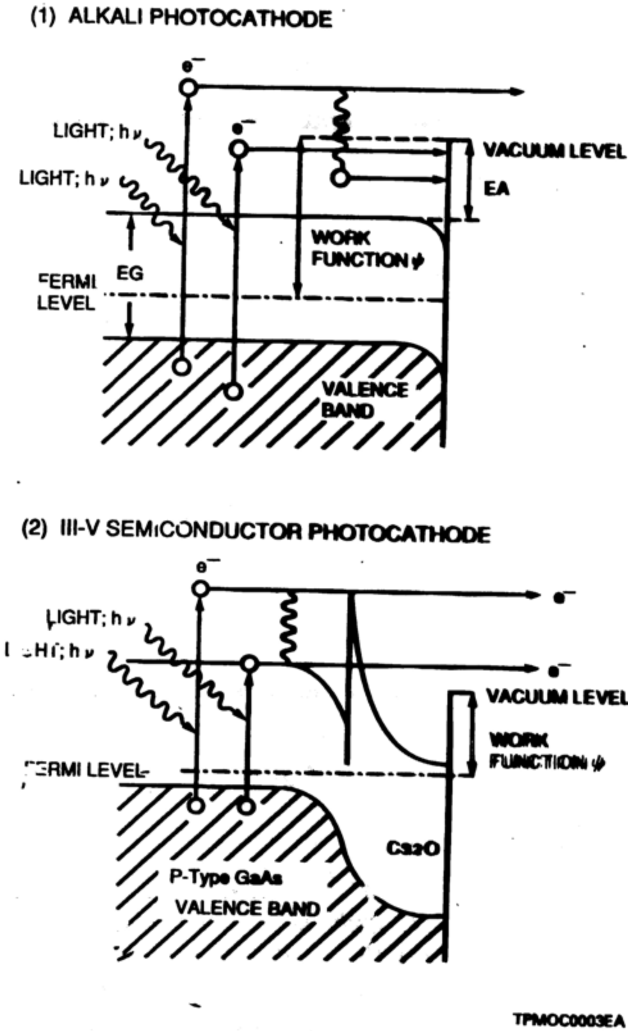


Fig.1 Spectral curves of standard photocathodes with lines of constant quantum efficiency, q, overlaid for reference

The Latest "Crystal Photocathode" Series




(1) ALKALI PHOTOCATHODE

(2) III-V SEMICONDUCTOR PHOTOCATHODE

TPMOC0003EA

Figure 2-2: Photocathode band models

$$\eta(\nu) = (1 - R)\frac{P\nu}{k} \cdot \left(\frac{1}{1 + 1/kL}\right) \cdot Ps$$

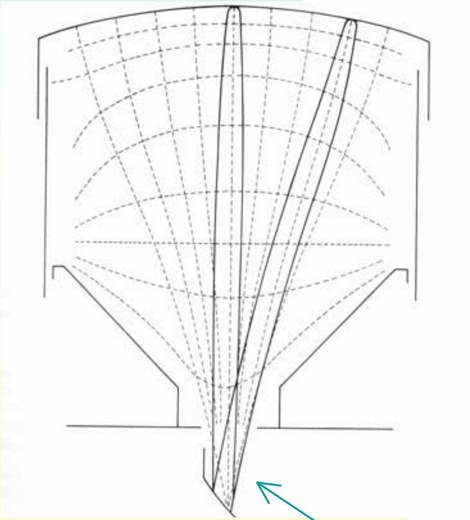
where

R : reflection coefficient
k : full absorption coefficient of photons
Pν : probability that light absorption may excite electrons to a level greater than the vacuum level
→ L : mean escape length of excited electrons
→ Ps : probability that electrons reaching the photocathode surface may be released into the vacuum
ν : frequency of light

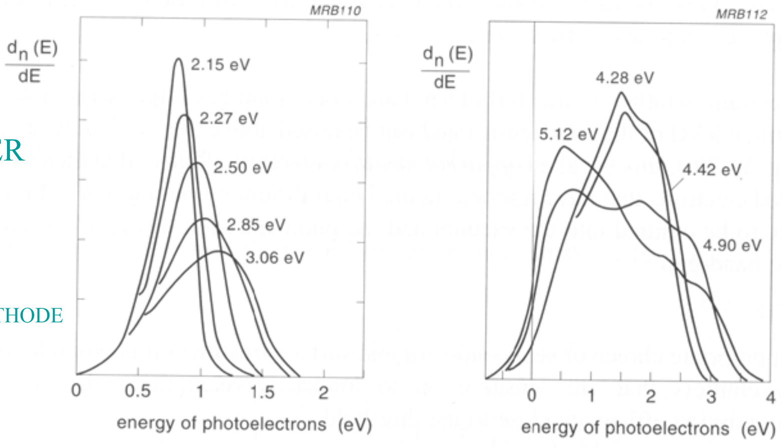
THE FRONT-END ELECTRON OPTICS

*FOCUSSES ELECTRONS ONTO SMALL AREA ELECTRON MULTIPLIER
(VERY IMPORTANT FOR LARGE PMTS)
*ACCELERATES ELECTRONS
•TIME SPREAD
•LOSSES (TRANSVERS MOMENTUM OF PHE)-> EFFECTIVE $QE<QE_{CATHODE}$
WAVE LENGTH DEPENDENT

EXAMPLE: POTENTIAL LINES AND ELECTRON TRACK BROADENING IN A LARGE PMT

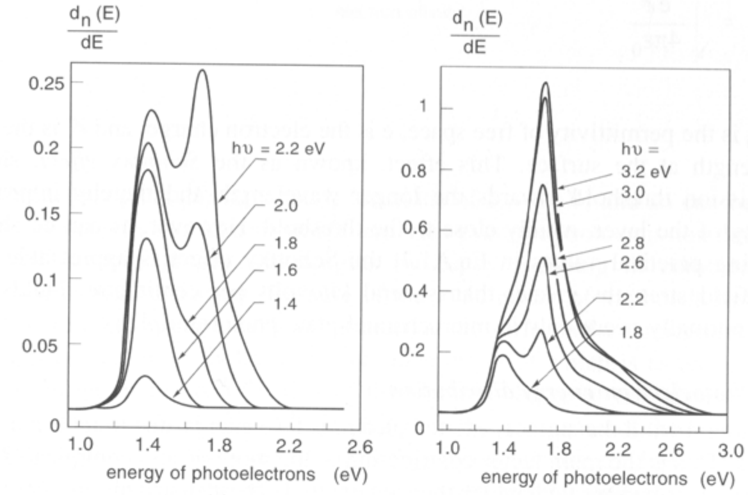


PHE CAN MISS DYNODE



(a) (b)

Fig.A1.8 Relative distribution of photoelectron energies, E_{ph}, from a layer of SbKCs at 290 K, for inciden photon energies (a) from 2.15 eV to 3.06 eV, and (b) from 4.28 eV to 5.12 eV

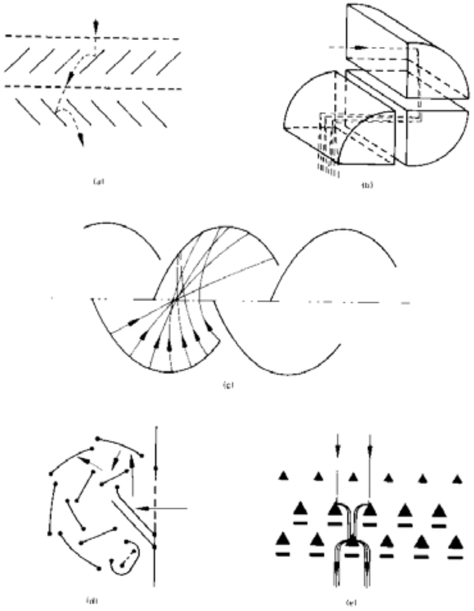


(a) (b)

Fig.A1.9 Photoelectron energy distribution (in electrons per photon per eV) from a layer of GaAs(Cs) for incident-photon energies (a) from 1.4 eV to 2.2 eV, and (b) from 1.8 eV to 3.2 eV

AMPLIFICATION IN A PMTS : DYNODE SYSTEM
GAIN UP TO FEW 10^6 POSSIBLE, NO CONT. TO NOISE

SOME DYNODE STRUCTURES



$G_{TOT} \approx (0.8 x G_I)^N$ N, G= number, gain of dynodes

Major secondary emissive materials[7)–21)] used for dynodes are alkali antimonide, beryllium oxide (BeO), magnesium oxide (MgO), gallium phosphide (GaP) and gallium arsenide phosphied (GaAsP). These materials are coated on a substrate electrode made of nickel, stainless steel, or copper-beryllium alloy. Figure 2-6 shows a model of the secondary emission multiplication of a dynode.

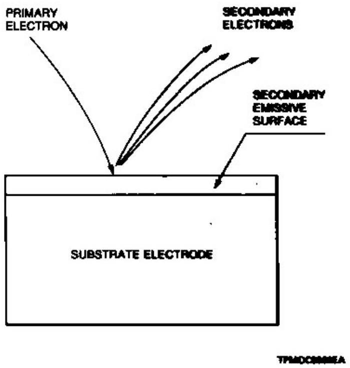


Figure 2-6: Secondary emission of dynode

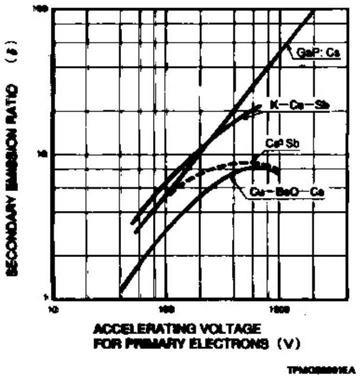
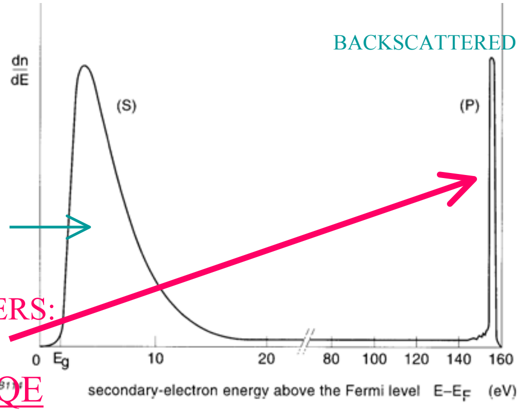


Figure 2-7: Secondary emission ratio

OTHER CONSTRUCTIONS ALSO IN USE
- •CHANNEL PLATES
- • ELECTRON BOMBARDED SEMICONDUCTORS



BACKSCATTERED ELECTRONS

IMPORTANT AT 1. DYNODE: FOCUSSING LOSSES

VERY IMPORTANT AND IGNORED BY NEARLY ALL USERS:
BACKSCATTERING LOSSES (10-30%) MATERIAL DEP.
EFFECTIVE QE IS NORMALLY SMALLER THAN QE

Fig.A1.11 Distribution of secondary-electron energies E above the Fermi level E_F.

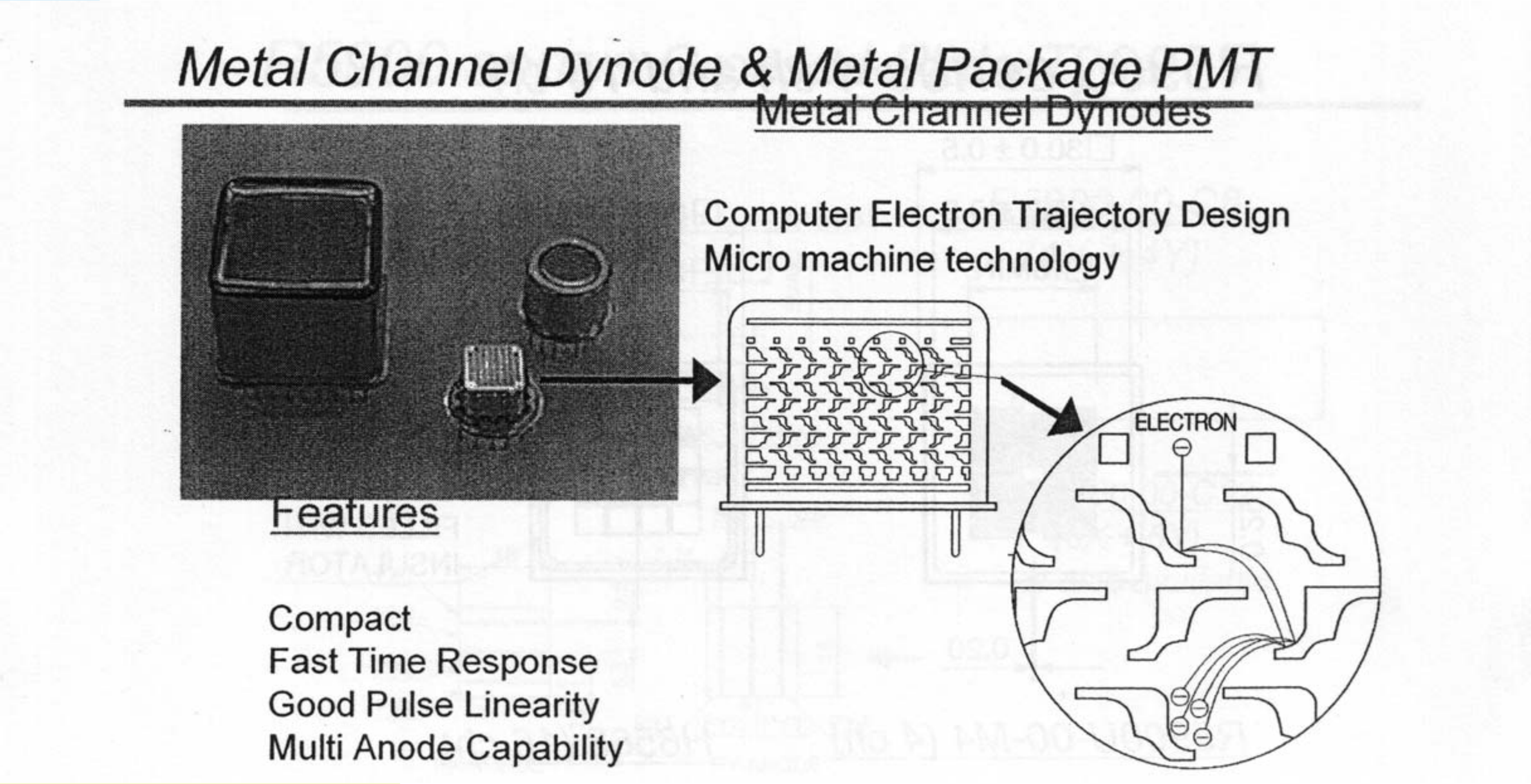
Breakthrough PMT Innovation Getting Ready For The Year 2000!

It's almost here. The next century PMT is almost on the scene. It's a new flat-shaped, super-thin light sensor called the "Flat Panel PMT". Innovative features of this new Flat Panel PMT include multielement connections and a large sensitive area guaranteed to open the door to dramatic scientific advances in the 21st Century.

FLAT PANEL
PMT

It compares with a HPK 2" diameter head-on photomultiplier tube.

[redacted]



Metal Channel Dynode & Metal Package PMT

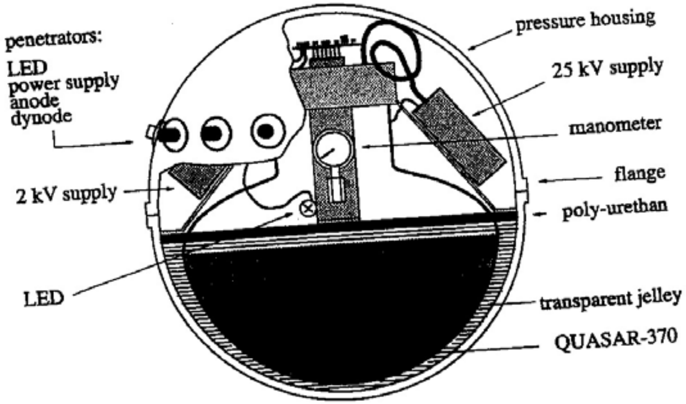
Metal Channel Dynodes

Computer Electron Trajectory Design
Micro machine technology

Features

- Compact
- Fast Time Response
- Good Pulse Linearity
- Multi Anode Capability

EXAMPLE OPTICAL MODULE OF THE BAIKAL LAKE NEUTRINO TELESCOPE



transit time distribution - ~2ns (FWHM) (~1ns)
(jitter)

single electron resolution - 70% (FWHM) (~40%)

Best tubes

Figure 2

EXAMPLE OF A SMART PMT :

THE QUASAR

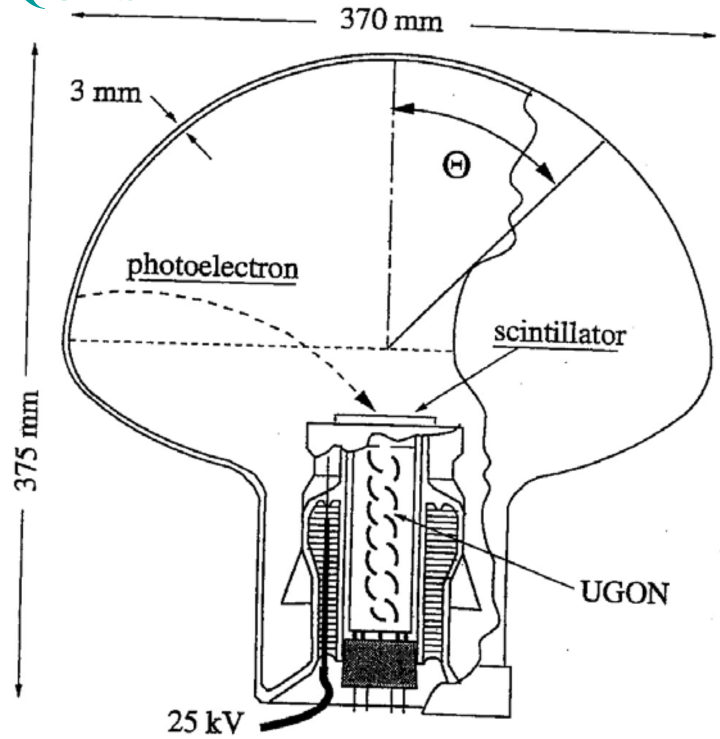
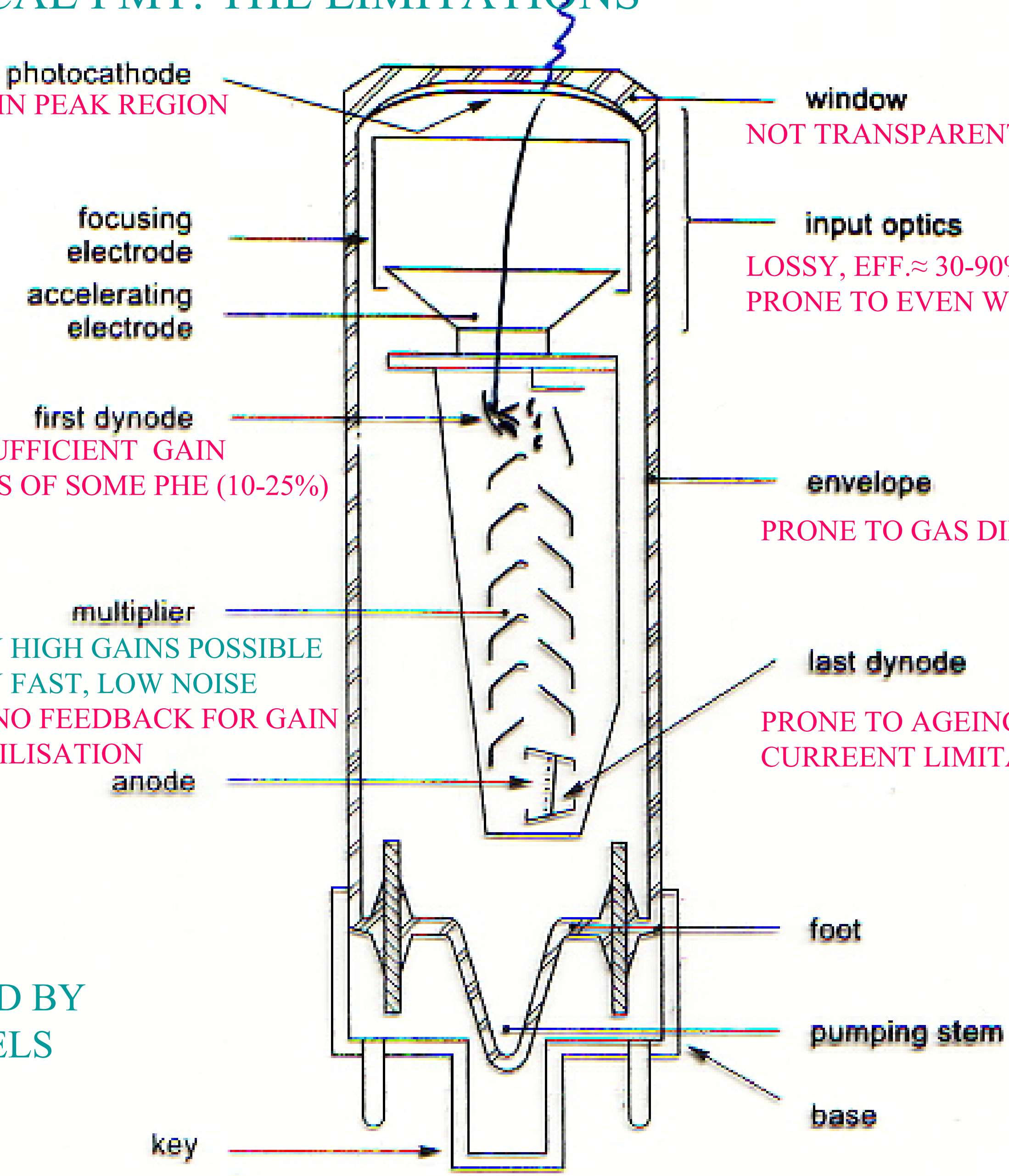


Figure 3

BASICALLY A LIGHT INTENSIFIER AND CONCENTRATOR

CAN BE IMPROVED WITH FASTER SCINTILLATOR: LSO, ZN
AND SiPMT FOR READOUT (D.FERENC, UC-DAVIS

A TYPICAL PMT: THE LIMITATIONS



QE ≈ 25% IN PEAK REGION

INSUFFICIENT GAIN
LOSS OF SOME PHE (10-25%)

VERY HIGH GAINS POSSIBLE
VERY FAST, LOW NOISE
BUT NO FEEDBACK FOR GAIN STABILISATION

NOT TRANSPARENT TO SHORT WAVE UV

LOSSY, EFF.≈ 30-90% (AT MOST)
PRONE TO EVEN WEAK MAGNETIC FIELDS

PRONE TO GAS DIFFUSION : HELIUM

PRONE TO AGEING, ION FEEDBACK
CURREENT LIMITATION

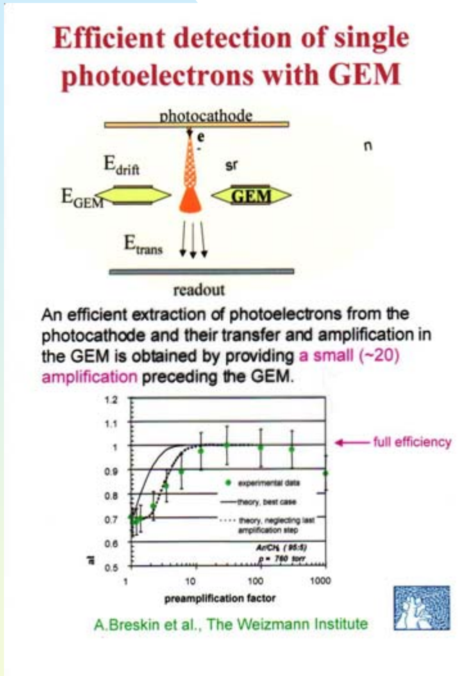
BULKY

EASILY DAMAGED BY
HIGH LIGHT LEVELS

GAS FILLED PHOTOMULTIPLIERS

MOST PHOTOCATHODES WORK IN ULTRAPURE NOBEL GASES

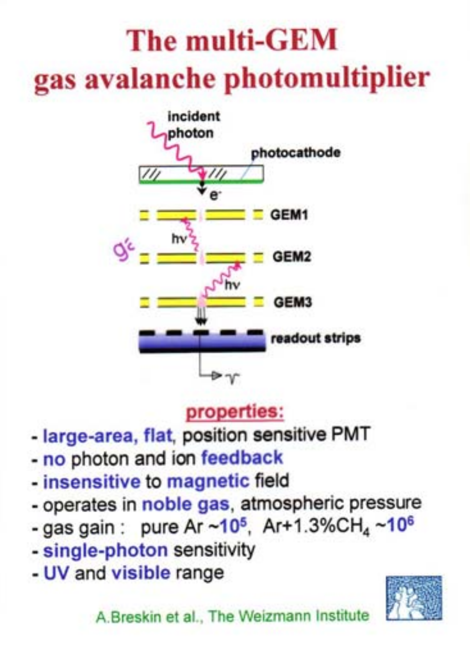
COMBINATION WITH SOME GASMULTIPLYING DEVICE (GEM, SAULI, et al)->PMT



Efficient detection of single photoelectrons with GEM

An efficient extraction of photoelectrons from the photocathode and their transfer and amplification in the GEM is obtained by providing a small (~20) amplification preceding the GEM.

A.Breskin et al., The Weizmann Institute

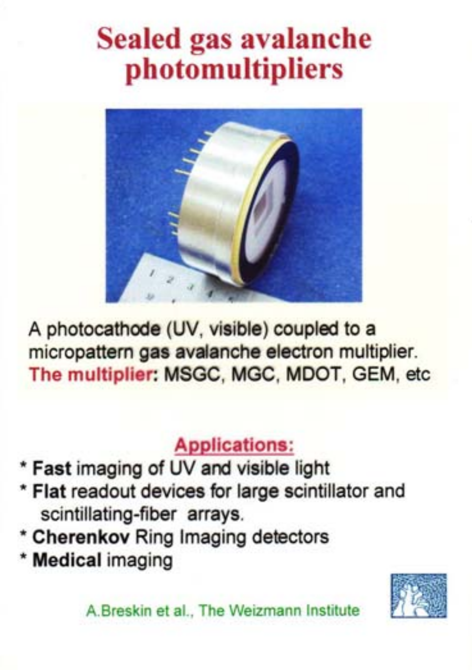


The multi-GEM gas avalanche photomultiplier

properties:

- **large-area, flat**, position sensitive PMT
- **no** photon and ion **feedback**
- **insensitive** to **magnetic** field
- operates in **noble gas**, atmospheric pressure
- gas gain : pure Ar ~10^5, Ar+1.3%CH_4 ~10^6
- **single-photon** sensitivity
- **UV** and **visible** range

A.Breskin et al., The Weizmann Institute



Sealed gas avalanche photomultipliers

A photocathode (UV, visible) coupled to a micropattern gas avalanche electron multiplier.

The multiplier: MSGC, MGC, MDOT, GEM, etc

Applications:

* **Fast** imaging of UV and visible light
* **Flat** readout devices for large scintillator and scintillating-fiber arrays.
* **Cherenkov** Ring Imaging detectors
* **Medical** imaging

A.Breskin et al., The Weizmann Institute

MAIN PROBLEMS: GASES ARE NORMALLY NOT PURE ENOUGH -LIMITED LIFETIME

PRODUCTION OF IONS THAT ARE ACCELERATED TOWARDS CAHTHODE -> DAMAGE, LINITED LIFETIME

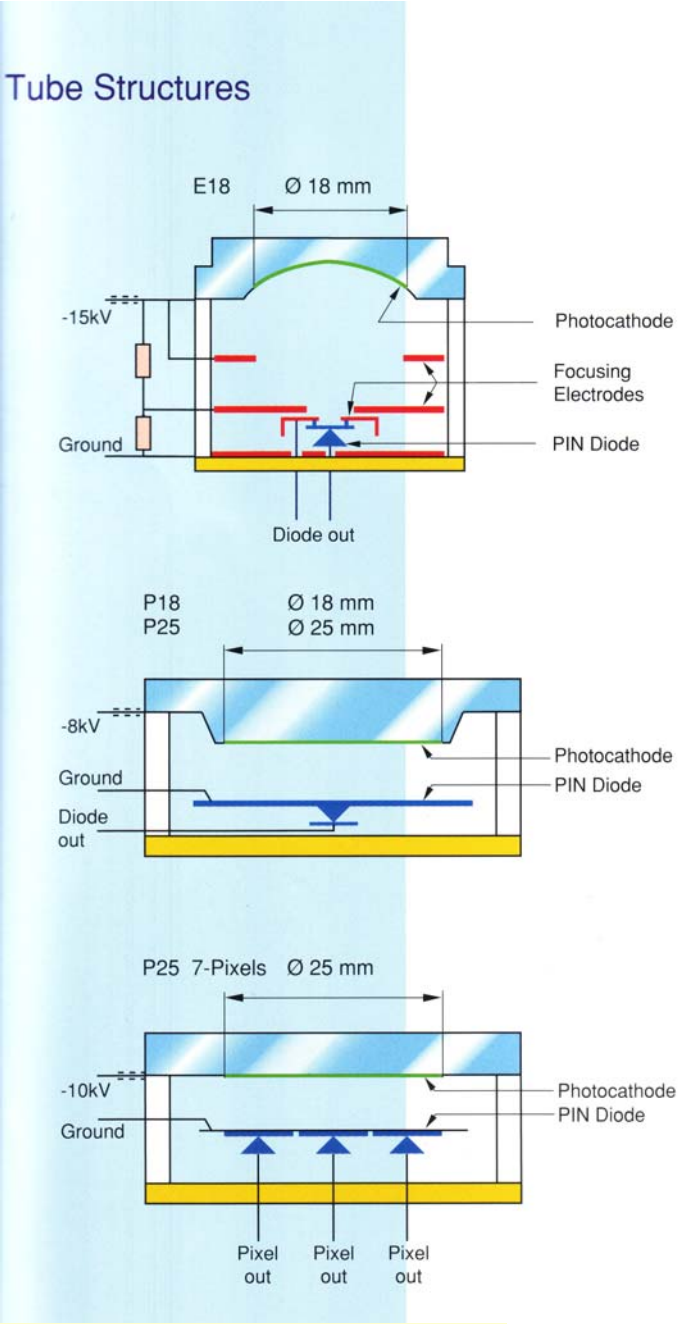
NO INTEREST FROM INDUSTRY

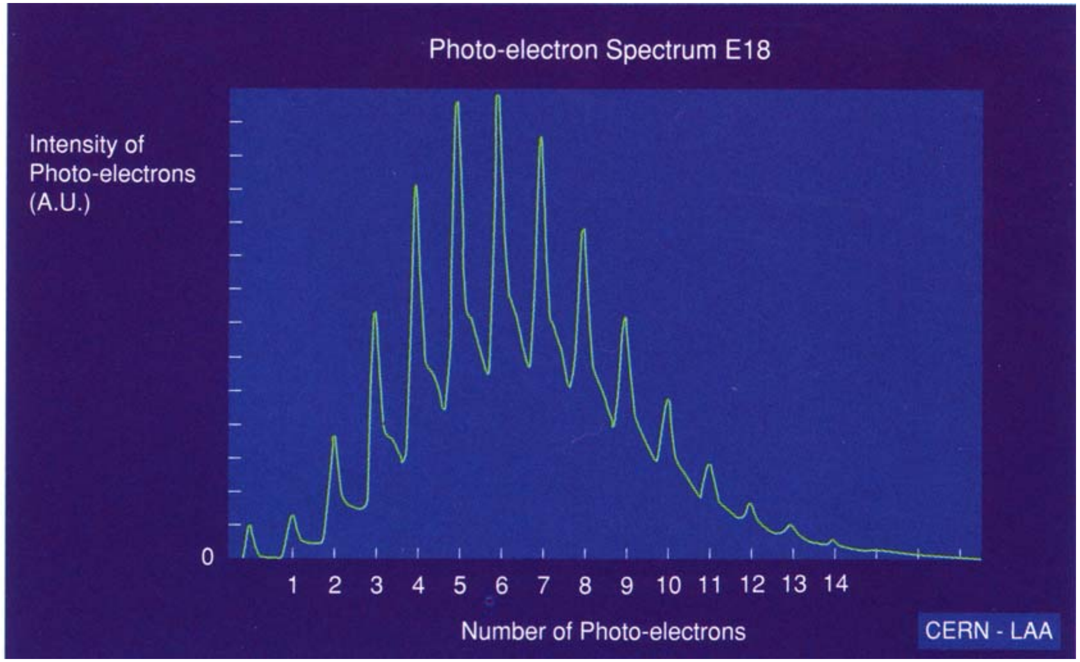
NEEDS COSTLY EQUIPMENT -> FEW GROUPS WORK ON THESE PROBLEMS

POTENTIAL TO MAKE MULTI m^2 DETECTORS STANDING ATMOSPHERIC PRESSURE

ELECTRICAL READOUT UNPROBLEMATIC

THE HYRID PMTS: REPLACE THE DYNODE SYSTEM BY A PIN DIODE (p-on-n STRUCTURE)
NEEDS VERY HIGH VOLTAGE
GAIN DUE TO ELCTRON-HOLE PRODUCTION IN DIODE
NEEDS CHARGE SENSITIVE PREAMP-> SLOW FOR GOOD SER (SINGLE ELECTRON RESPONSE)





THE AVALANCHE PHOTODIODE

NEARLY 80% QE

GAIN 50-10000

HIGH EXCESS NOISE FACTOR->NO SER

NOISE: A FEW e

NOT YET OK BUT PROMISING

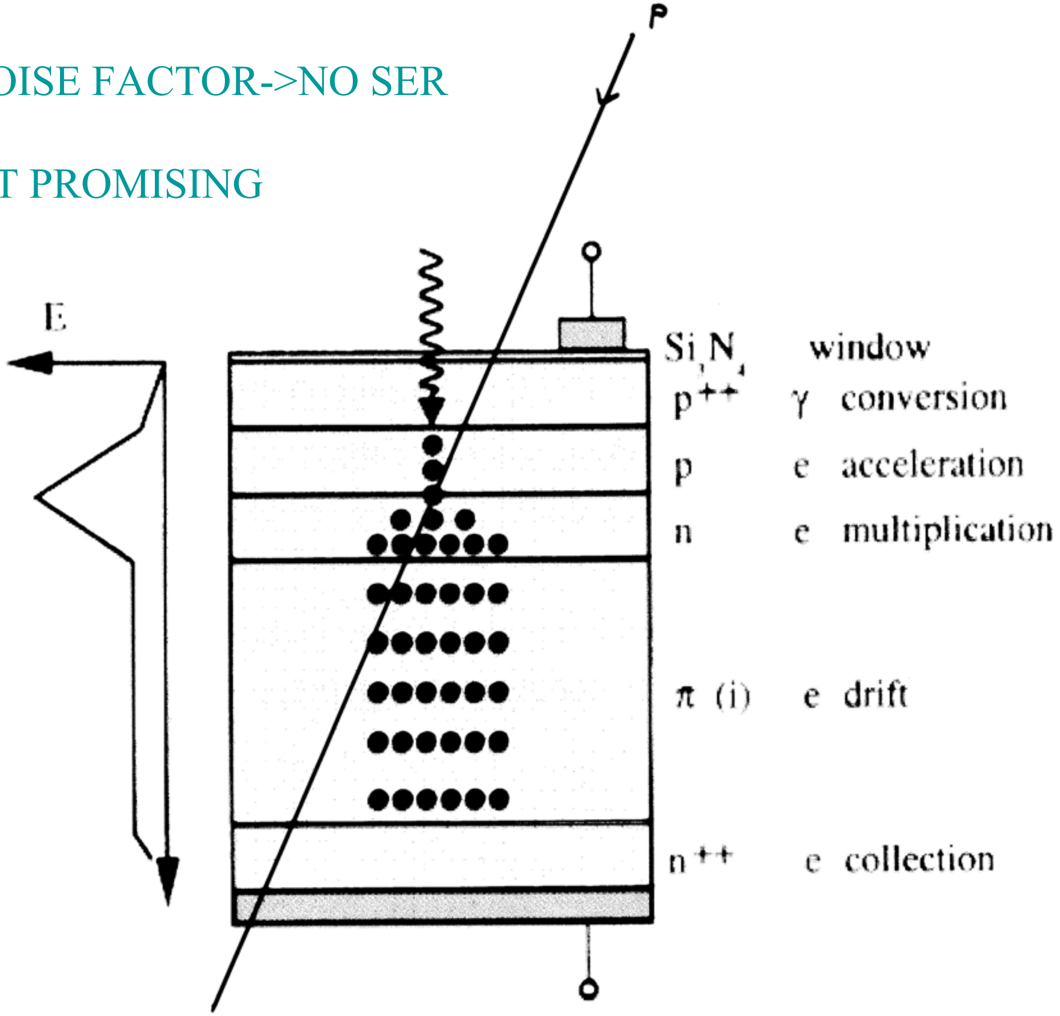


Fig. 2. APD working principle and Nuclear Counter Effect.

THERE IS A CLEAR NEED FOR BETTER PHOTON DETECTORS (HIGHER QE, LARGER ACTIVE AREA, CHEAPER, FASTER, MORE ROBUST,FINER PIXELS)

EXPERIMENTS THAT WILL BE BETTER OR ONLY THAN FEASIBLE

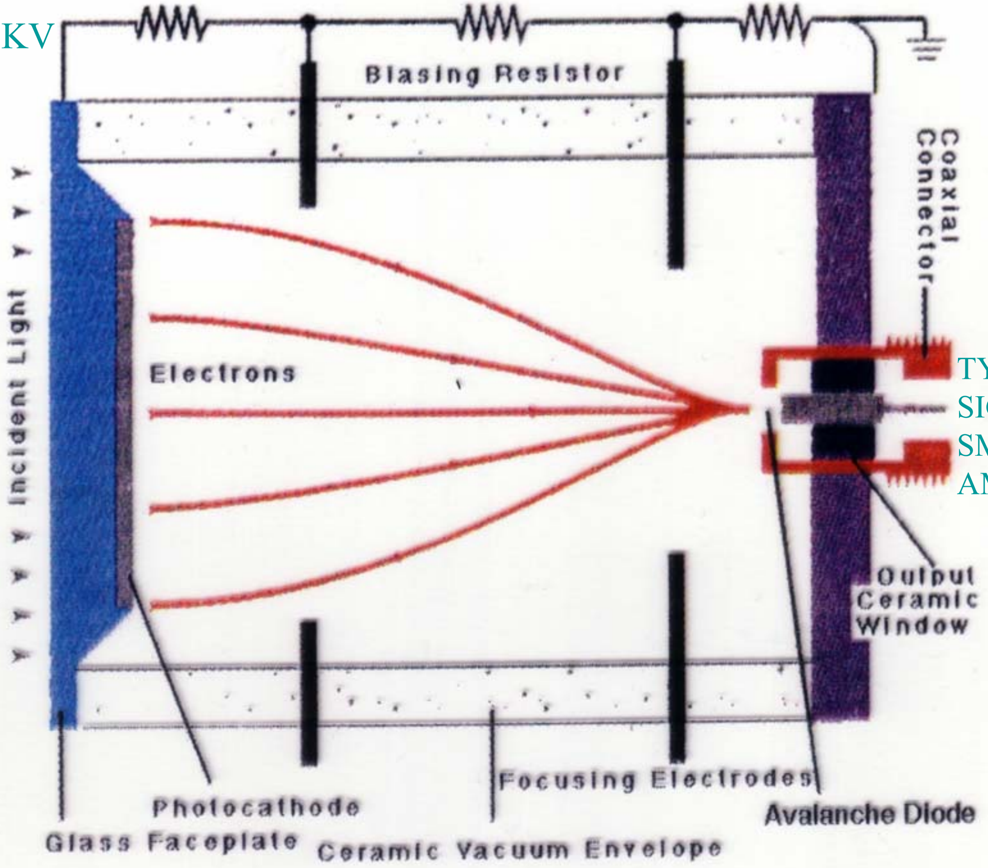
EXAMPLES:
- EUSO
- LARGE VOLUME (>>1 km^3) NEUTRINO DETECTORS
- NEXT GENERATION GROUND-BASED AIR CHERENKOV TELESCOPES FOR GAMMA-ASTRONOMY
- LOWER THRESHOLD GROUND BASED FLUORESCENT DETECTORS

- STAGNATION OF THE DEVELOPMENT FOR LARGE PHOTON DETECTORS FOR MANY DECADES
- (HEP: NO MORE NEED. INDUSTRY TURNED TO SOLID STATE DEVICES, MINIATURISATION, DEVELOPMENTS EXPENSIVE, NO COMMERCIAL MARKET FOR PHOTON DETECTORS, EX MEDICAL APPL.)
- WE SEE NOW NEW ACTIVITIES IN THE DEVELOPMENTS, PARTLY TRIGGERED BY NEED OF HIGH ENERGY ASTRO PARTICLE PHYSICS

PRINCIPLE OF HYBRID PMT: PHOTOELECTRONS WILL BE ACCELERATED IN STRONG ELECTRICAL FIELD HIT SEMICONDICTOR AVALANCHE DIODE-> e-hole PRODUCTION, ELECTRONS WILL BE FURTHER AMPLIFIED IN AVALANCHE DIODE

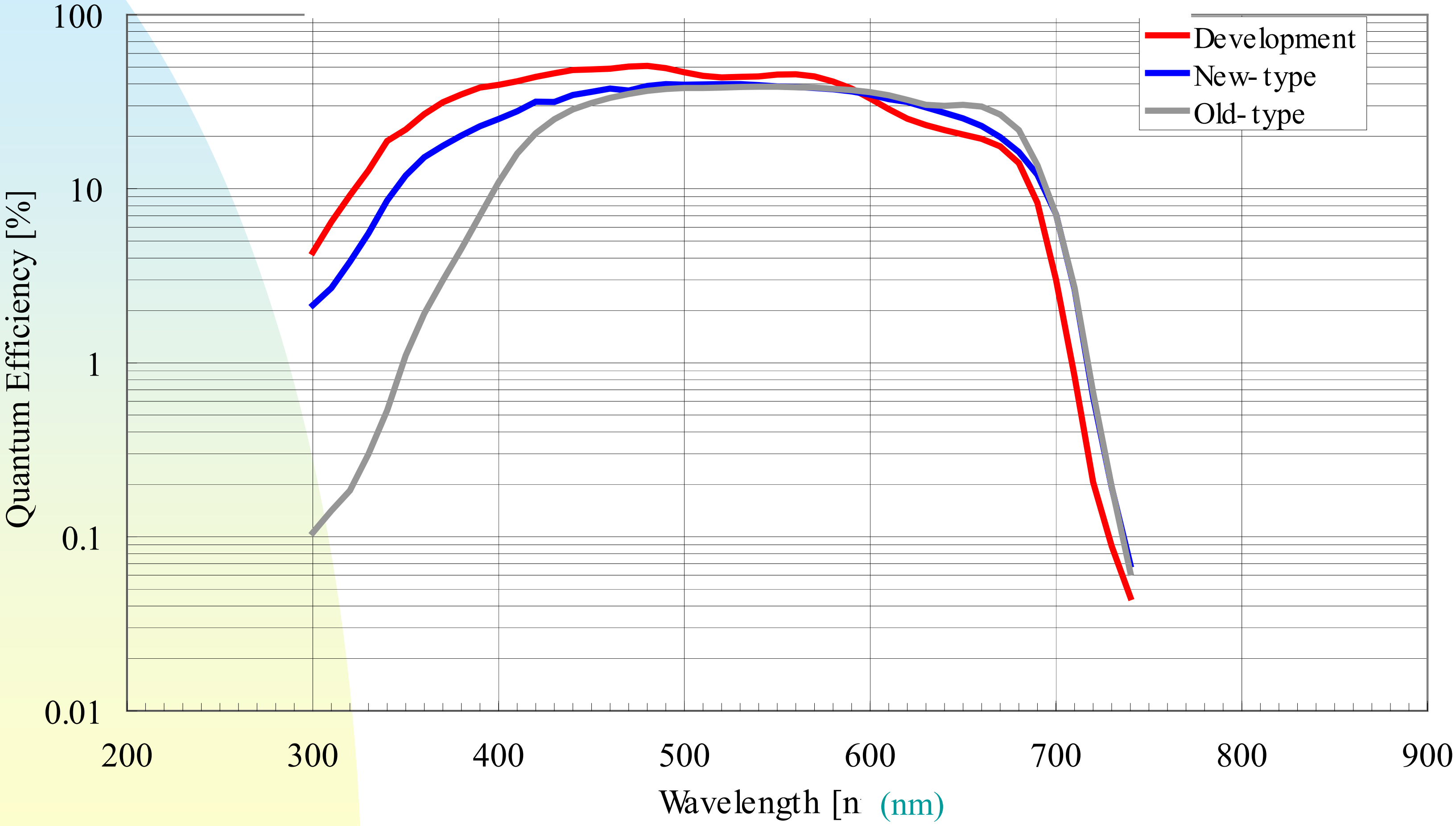
GAIN = ((U - Umin)/ 3.6 eV) x AVALANCHE GAIN,   U IN VOLTS

-5 TO -10KV



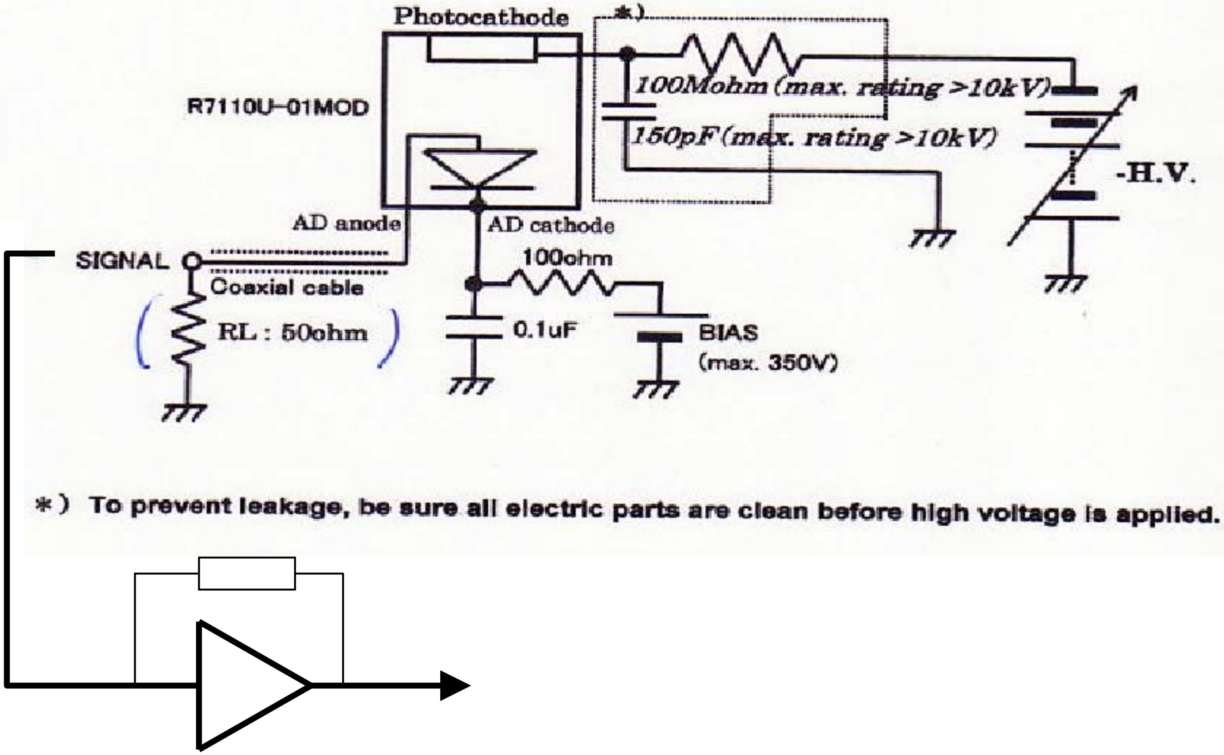
TYP GAIN 10 000 TO 80 000
SIGNAL STILL VERY
SMALL, NEEDS ADDITIONAL
AMPLIFICATION

QUANTUM EFFICIENCY OF GaAsP CATHODES OF DIFFERENT DEVELOPMENT STEPS



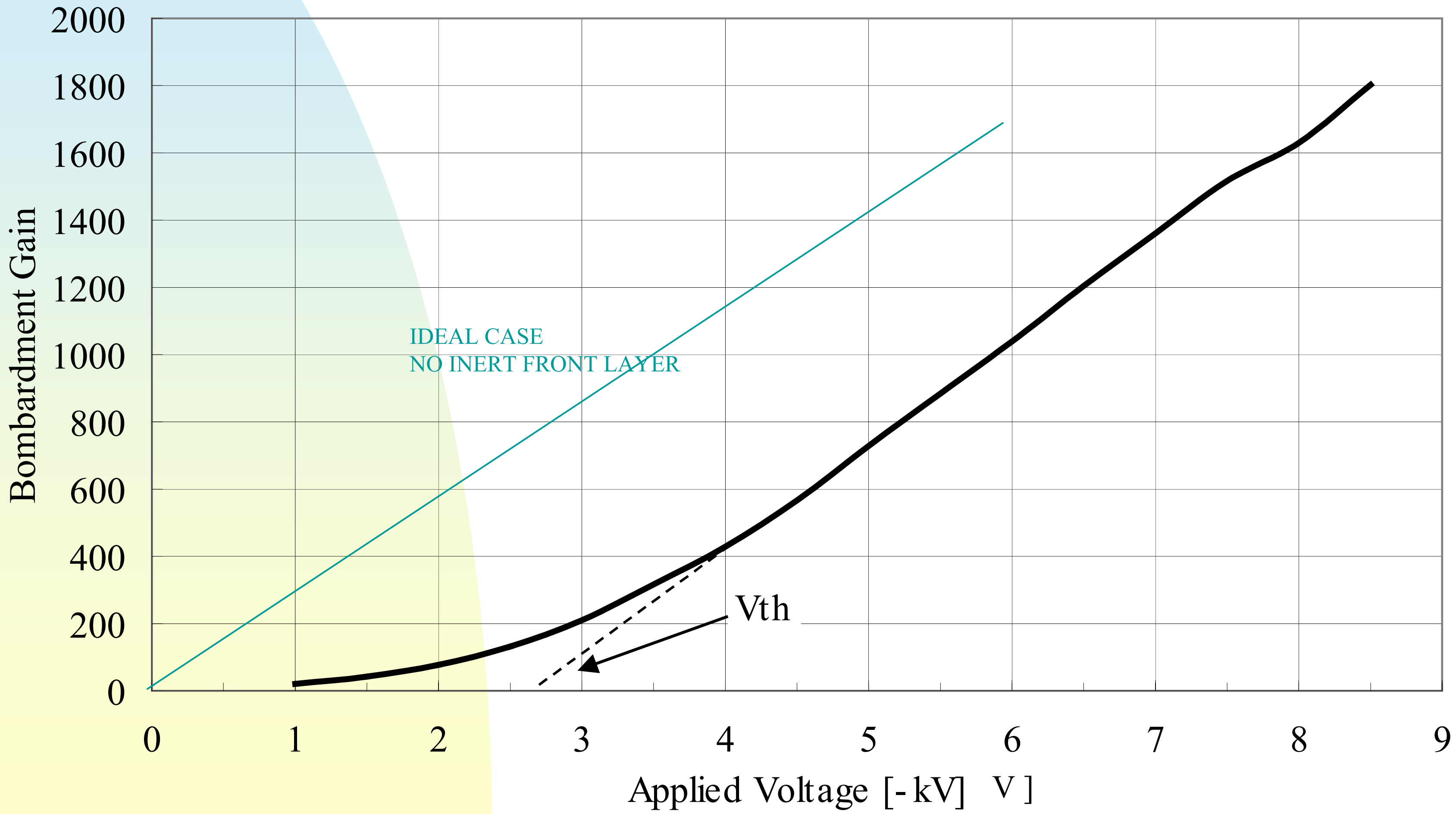
MODE OF OPERATION FOR FAST SIGNAL DETECTION: USE OF FAST TRANSIMPEDANCE AMP OR VOLTAGE AMP

High Speed Light Detection Mode



*) To prevent leakage, be sure all electric parts are clean before high voltage is applied.

THE GAIN CHARACTERISTICS OF THE HYBRID PMT WITH THE NEW LOW CAPACITANCE AVALANCHE DIODE



(2003 VERSION)

Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

SER RESPONSE FOR DIFFERENT POST AMPLIFICATION

3 pe

CSA CANBERRA 2003 BT
10 NSEC DIFF.

1 pe

Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

P

3 pe

1 pe

CSA CANBERRA 2003 BT
10 NSEC DIFF.,10 NSEC INT

Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

P

3 pe

1 pe

Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

P

1 pe

3 pe

FAST VOLTAGE
AMP

Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

THE GEIGER MODE MULTICELL APD (=SiPMT)

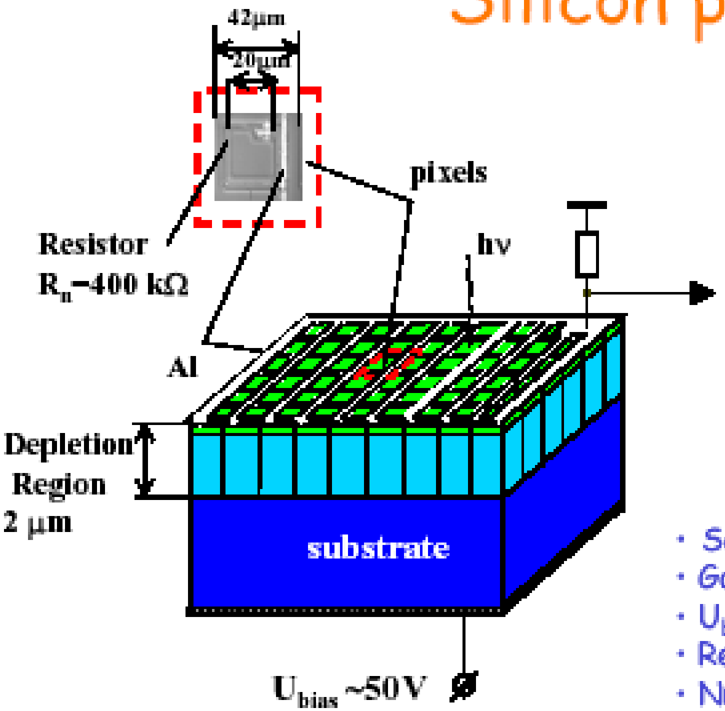
VERY PROMIZING ALL SOLID STATE CANDIDATE FOR A HIGH QE FAST PHOTON DETECTOR

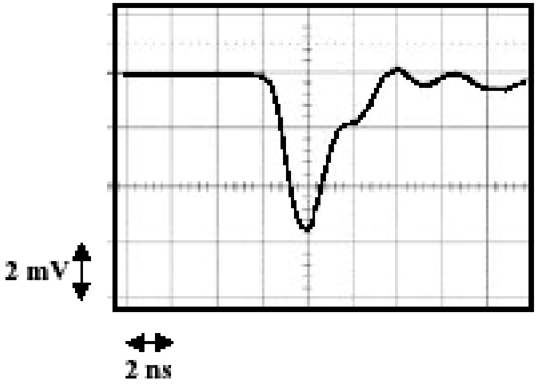
- GOOD SER
- SIMPLE TO OPERATE
- RELATIVELY CHEAP TO PRODUCE
- NOT AFFECTED BY MAGNETIC FIELDS
- ROBUST

- HIGH NOISE RATE
- STILL ONLY SMALL AREA

PIONEERING WORK BY
B. DOLGOSCHEIN
V. GOLOVIN
S. SADYGOV

Silicon photomultiplier (SiPM)



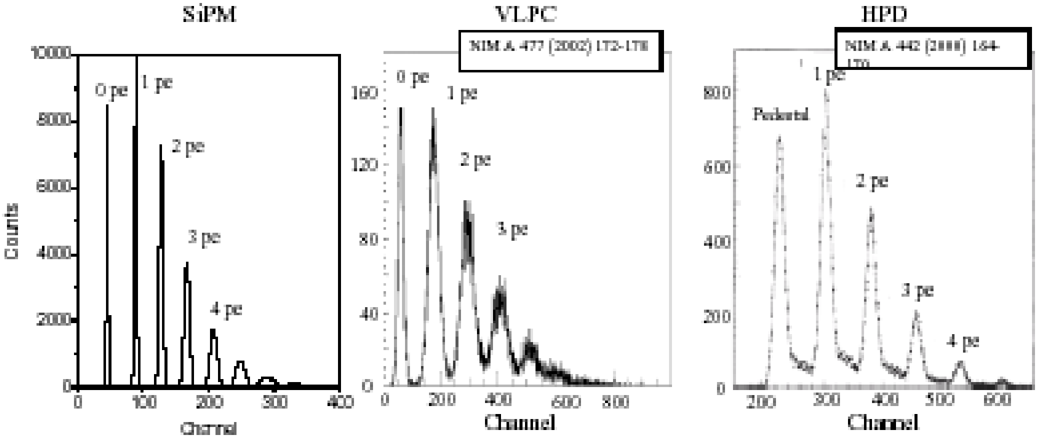


SiPM main features:

- Sensitive size 1x1mm^2 on chip 1.5x1.5 mm^2
- Gain $2\cdot10^6$
- U_{bias}~50V
- Recovery time ~ 100 ns/pixel
- Number of pixels: 576
- Nuclear counter effect: negligible (due to Geiger mode
- Insensitive to magnetic field
- Dynamic range ~10^3/mm^2

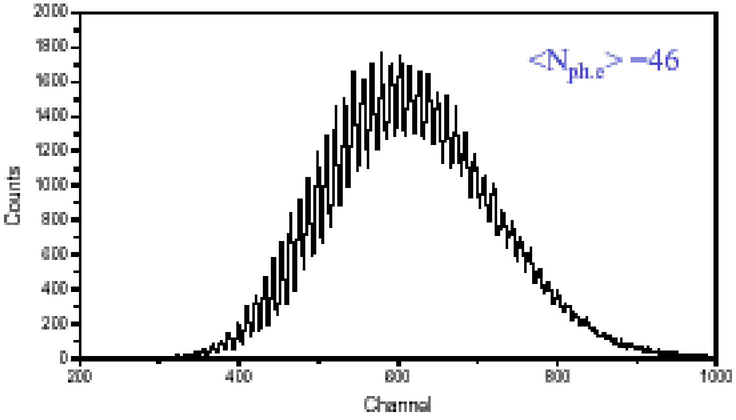
For further details see:
«Advanced study of SiPM»
http://www.slac.stanford.edu/pubs/icfa/fall01.html

Single photoelectron (single pixel) spectra



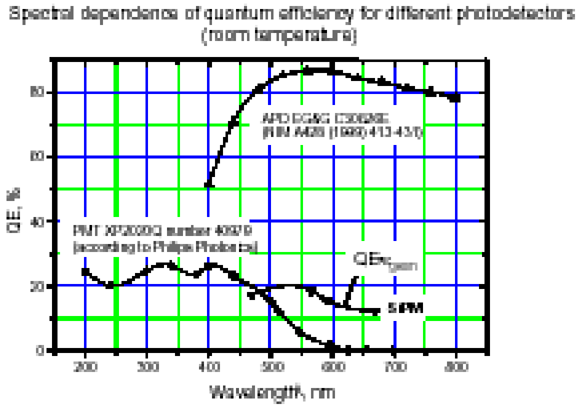
SiPM:
- excellent single photoelectron resolution
- low ENF expected

More about pixel signal resolution: tens of photoelectrons



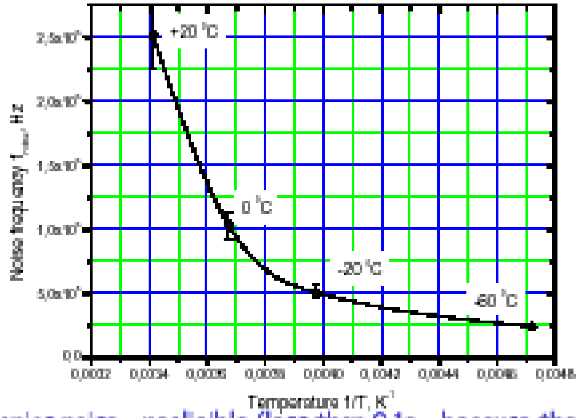
- SiPM consists of a large number of pixel photoelectron counters with binary readout for each pixel, working as analogue device
- signal uniformity from pixel to pixel is quite good

Photon detection efficiency



SiPM: $\varepsilon = QE \cdot \varepsilon_{geom}$, $\varepsilon_{geom} \sim 0{,}3$ (possible improvement up to ~ 0,5)

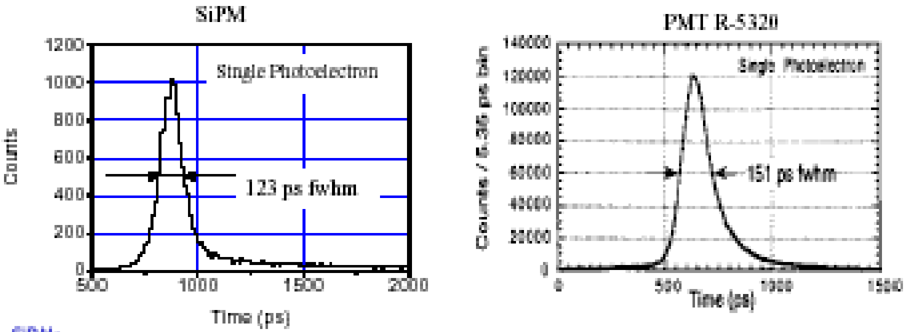
SiPM noise



- Electronics noise - negligible (less than 0,1e - because the SiPM gain ~10^6)
- dark rate noise

Even for room temperature the contribution of the dark rate is rather low (less than 1 ph.e. for a gate of 50 ns)

Timing by SiPM: possible application for Cherenkov Imaging Counters



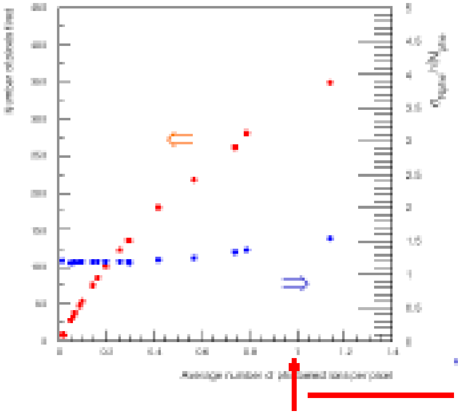
SiPM:
- position sensitive (~1 mm²)
- a single photon detection capability with background hits density : $2 \cdot 10^{-3}$ 1/ns·mm² (room temperature)
  $3 \cdot 10^{-4}$ 1/ns·mm² (-50°C)
- insensitive to magnetic field
- good time resolution (~50 ns rms)

FWHM: Laser (40 ps) + electronics (60 ps) => SiPM (100 ps)

SiPM dynamic range

Dynamic range is limited due to finite total number of pixels *m*

Signal ~ $m(1-\exp(-N_{ph.e}/m))$



"Dispersion limit" of dynamic range:
$N_{ph.e}/m < 1$