ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2016. Т. 47. ВЫП. 6

EVOLUTION OF IDEAS IN PHOTON DETECTION

B. K. Lubsandorzhiev [*]

Institute for Nuclear Research of the Russian Academy of Sciences, Moscow

In this paper, we consider the evolution of ideas in vacuum photodetector developments. Diverse approaches in developments of vacuum photodetectors (classical photomultipliers and hybrid phototubes) for the last half of century are covered. A particular emphasis is made on large area vacuum photodetectors developments. Some other issues concerning WLS and light guide techniques for increasing photodetectors sensitivity are highlighted as well.

PACS: 85.60.Ha

INTRODUCTION

Marcel Proust once wrote: *“The real voyage of discovery consists not in seeking new landscapes but in having new eyes”* [1]. These great Frenchman’s words are quoted not casually here. Developments of new experimental instruments always provide new opportunities for scientific endeavors and open roads to discoveries. My great teacher Aleksandr Evgen’yevich Chudakov liked to say that every physics experiments should develop new experimental techniques which in their turn will bring experiments to great discoveries and new understanding of Nature. Photon detectors are an exemplary case for this claim.

Indeed, photon detectors play key roles in the overwhelming majority of present-day physics experiments, in high energy and astroparticle physics experiments, in particular. It would not be an exaggeration at all to claim that photon detectors are a real “workhorse” in Nature studies. For a long long time human beings studied Nature using just “natural” photon detectors — their eyes. Human eye is one of evolution’s summits which puzzled Charles Darwin. It should be noted that it is not perfect summit because it has some evolutionary inherited shortcomings but still it is a very good photon detector with 576 Mega pixels. For the most part of human beings history, human eye was the only photon detector. A bit more than 400 years ago humans started to invent instruments to

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[*] E-mail: lubsand@rambler.ru

help their eyes — lens, telescopes, and microscopes. Galileo Galilei revolutionized experimental observations using telescope. Even in the 20th century some great fundamental breakthroughs in physics, like discovery of atomic structure by H. Geiger and E. Marsden [2, 3] in 1908–1909 and discovery of Cherenkov Effect by P. A. Cherenkov and S. N. Vavilov [4, 5] in as late as 1933, were made with just naked eyes. The former was made by detecting light pulses produced by α particles in ZnS luminescent screen and the latter — by registering visible photons produced in transparent liquids by relativistic particles from radioactive sources.

It is worth noting that even Albert Einstein was awarded with the Nobel Prize for his explanation of photoeffect as it was formulated by the Nobel Committee: "for his services to theoretical physics, and *especially for his discovery of the law of the photoelectric effect*" [6] (here is my (*B.L.*) Italics).

Invention of vacuum photoelectron multipliers by great Soviet physicist and engineer A. L. Kubetsky [7] in the late 1920s — early 1930s opened new "modern" era in physics experiments. High gain and relatively high sensitivity of photomultipliers made them immediately very popular in physics experiments. Unfortunately, as nearly as all great inventions and discoveries, photomultiplier invention is wrapped in foggy controversies. I would like to refer to [8] for more details on the issue. Those controversies follow practically all developments in photon detection. We will try to hightlight some of them in the following sections of the paper.

1. HYBRID PHOTOTUBES

At the early stages of their development PMTs suffered from many shortcomings. The most prominent of them were low values of secondary emission coefficient of dynode materials, the first dynode materials, in particular. The latter value is of most importance in photon detection because it is directly connected with absolute sensitivity of photomultipliers. Even now many experimentalists refer to quantum efficiency of photocathode, in most cases provided by PMTs manufacturers, to evaluate absolute sensitivity of their photomultipliers. In reality, in order to know how many photons hit photon detector, one needs to know not only photocathode quantum efficiency but also how effectively photoelectrons produced at the photocathode are detected by photoelectron multiplying system or dynode system as in case of classical photomultipliers. In turn, the photoelectron detection efficiency of multiplying system depends on how photoelectrons are collected on to multiplying system and how effectively they are multiplied by it. Indeed, even though photoelectrons are successfully collected on multiplying system there should be a probability for photoelectrons to perish on it not giving any secondary electrons. In case of dynode system, the less secondary emission coefficient of the first dynode the higher probability for photoelectrons not to be detected and the less photon detection efficiency. To improve photon detection efficiency of vacuum photodetectors, Hybrid Phototubes using silicon diodes (Hybrid Photo Diodes) and scintillator crystals (Hybrid Phototubes with Luminescent Screens) for photoelectrons multiplication have been developed.

1.1. Hybrid Photo Diodes. In 1957, N. Sclar and Y. C. Kim [9] tested an electron bombarded silicon-diode as electron multiplication system. Indeed, the idea was compelling. The energy needed for one pair of carriers in silicon is about 3 eV, so, 10-keV electron should produce more than 3000 electron-hole pairs resulting in gain of more than 3000. They applied 16 kV to their test tube and really reached gain of several thousand per one initial electron. These results instigated researchers to use silicon diodes for photoelectron multiplication. In the mid-1960s J. M. Abraham with his colleagues [10] and R. Kalibjan [11, 12] did a lot of experiments with hybrid phototubes with silicon diodes. Unfortunately, they did not manage to develop hybrid phototubes with discernible single-photoelectron peak in their charge distribution. The most difficult problem, unsolvable at that time, was influence of photocathode manufacturing process on the silicon diode characteristics — the leakage current of diodes increased and the phototubes gain deteriorated substantially during and after photocathode deposition. The lucky man who succeeded in production of hybrid phototube with silicon diode was Ph. Chevalier. He managed to develop the first hybrid phototube with silicon diode which had really very good single-photoelectron resolution [13, 14]. His phototube was equipped with metallic photocathode to avoid the above-mentioned problem and silicon diode. High voltage of ~ 18 kV was applied to photocathode. The drawing of the Chevalier's phototube is shown in Fig. 1, *a*. The first excellent separation of 1, 2, 3, etc. photoelectron peaks are clearly seen in the charge distribution of multi-photoelectron pulses, Fig. 1, *b*.

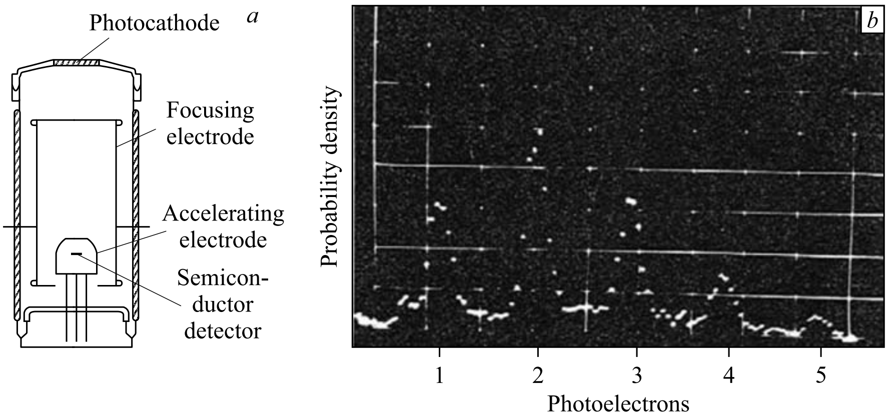


Fig. 1. Hybrid photodiode developed by O. Chevalier [13, 14]

Presently it is not completely clear for what reason such phototubes did not get further development for the succeeding nearly two decades. It might be that the problem of silicon diode parameters deterioration during photocathode manufacturing process was too formidable at that time. Anyway, only in 1987 a paper on the development of such phototubes named Hybrid Photo Diode (HPD) was published. It was the Cornell University's preprint published by R. DeSalvo [15]. In that preprint R. DeSalvo claimed, quite erroneously, invention

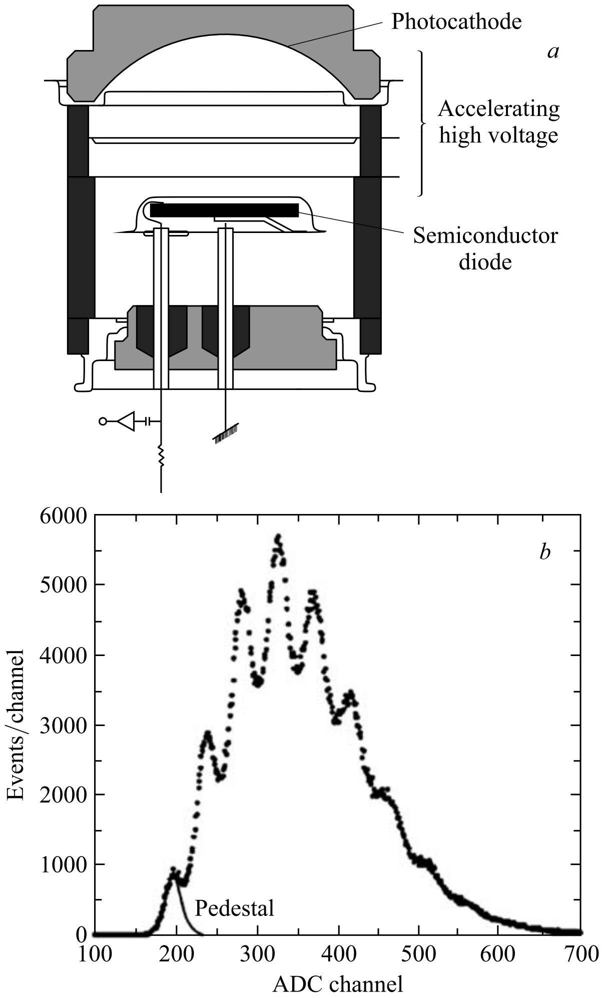


Fig. 2. Hybrid Photo Diode developed by R. DeSalvo [15, 16]. *a*) HPD's drawing; *b*) HPD's multi-photoelectron charge distribution

of a “new type” photon detector. Just in the paper published several years after the first preprint R. DeSalvo corrected his mistake [16]. He wrote in his paper [16] that *“For a period of time it was thought that one of us* (*R. D.* [Ricardo DeSalvo]) *had been the first to conceptualize such a detector. It was later realized that this principle of operation had already been investigated and set aside several times for reasons unknown to us... ”* Anyway, as far as I know, R. DeSalvo was the first who coined the name Hybrid Photo Diode (HPD). The drawing of his HPD is shown in Fig. 2, *a*.

The tube utilizes inverse image focusing electron optics like in the first-generation image intensifier. A “transfer” technique was used for the tube photocathode manufacturing process and silicon diode installation and final assembling of the tube. It allowed avoiding problems of diode parameters deterioration which previous experimenters encountered with. With this tube R. DeSalvo and his colleagues reached rather good distinctions between peaks due to different numbers of photoelectrons, as demonstrated in Fig. 2, *b*. Further works on that tube resulted in the rapid development of HPDs for the LHC experiments together with DEP Company. Some developments were done on position-sensitive HPDs with segmented silicon diodes [17]. As in Chevalier’s case photoelectrons accelerating high voltage of more than 10 kV were applied to photocathode. This fact was the reason of problems physics encountered with during exploitation of the tubes in experiments.

HPD with avalanche silicon diode and negative electron affinity (NEA) AsGaP photocathode has been developed for the second stage of the MAGIC Telescope project. In this phototube, to avoid bombardment of photocathode (NEA photocathodes are particularly vulnerable to this effect) by ions due to ionization of residual gas atoms, special technical efforts were introduced for trapping such ions [18]. Avalanche diode increases the phototube total gain and improves its timing parameters. Here once again photocathode is under high voltage of more than 10 kV. It will encumber further use of the HPD.

The idea of HPD has undoubtedly many advantages but it should be noted it imposes additional problems connected with necessity to ground the photocathode and apply accelerating high voltage of many kilovolts to the anode. Experimentalists involved into large-scale neutrino experiments pay attention to the development of large sensitive area HPD with large hemispherical photocathode and large area pin silicon diode or avalanche silicon diode [19, 20]. In this kind of applications, where phototubes immersed into water, it is absolutely impossible to keep the phototube’s photocathode under high voltage. So one needs to ground photocathode and put high voltage to the anode region where silicon diode is located. The problem is how to separate anode under high voltage and silicon diode without distorting electron optics. It seems these technical problems are being somehow solved.

1.2. Hybrid Phototube with Luminescent Screen. From many points of view, it is much easier to use the other approach, which is exploited for many years in image intensifiers or, if one does not need to make images, light amplifiers. The first electro-optical converters were developed in the early 1930s (e.g., Holst's cup [21, 22] — electro-optical converter with the first proximity focusing electron optics). In this approach photoelectron from photocathode is accelerated by high voltage (> 10 kV) and hits luminescent screen (thin layer of a crystal scintillator or a phosphor) producing light flashes in it. So, one photon at the photocathode can produce many photons in luminescent screen. The first image intensifiers based on this idea were very rapidly developed and the first night vision goggles were intensely used already even in the Second World War.

Great soviet physicist E. K. Zavoysky with his colleagues did tremendous job developing a number of image intensifiers for use in physics experiments, e.g., for registering kinetics of fast physics processes [23].

Image intensifiers were used actively in cosmic ray physics as early as 1940s and 50s to detect images of extensive air showers. In 1957–1958 my great teacher A. E. Chudakov did first attempts to build large area photodetector with hemispherical photocathode and luminescent screen viewed by conventional small photomultiplier but failed to find fast high efficiency scintillator. He experimented with phosphors like ZnS and gave up his efforts soon [24] due to mostly poor quality of phosphors. In the following two decades interest from physics experiments seemed expired but nonetheless image intensifiers had been developed rampantly winning medical market — mostly large area X-ray image intensifiers. A number of new very fast scintillators with sufficiently high light yield have been developed. Scintillators for such applications besides fast emission kinetics and high light yield should withstand vacuum and high temperature and alkali influence during glass baking and photocathode manufacturing procedures. For more detail on scintillators we relegate to our paper [25].

It seems by the end of the 1970s all conditions ripened for a breakthrough — proper scintillator materials, vacuum technologies, on the one hand, and on the other hand, growing demands from physics experiments. In the early 1970s new large-scale experiments in neutrino and cosmic ray physics have been intensely discussed and even started to be implemented. Deep underwater neutrino telescopes needed urgently large sensitive area photodetectors for viewing large volumes of natural water — in ocean (DUMAND [26] project near Hawaii) and lakes (BAIKAL [27] at Lake Baikal). In initial discussions of the DUMAND project the total number of large area photodetectors was proposed to be ~ 20 thousands.

At the very beginning of the 1980s, D. Winn and C. Rubbia pushed forward an idea of very large sensitive area photodetector — "barrel-like" hybrid photodetector [28]. A conceptual drawing of their hybrid phototube is shown in Fig. 3. Their idea was to use light amplification principle. The photodetector's glass envelope is a glass cylinder, 1 m long and 40 cm in diameter. On the

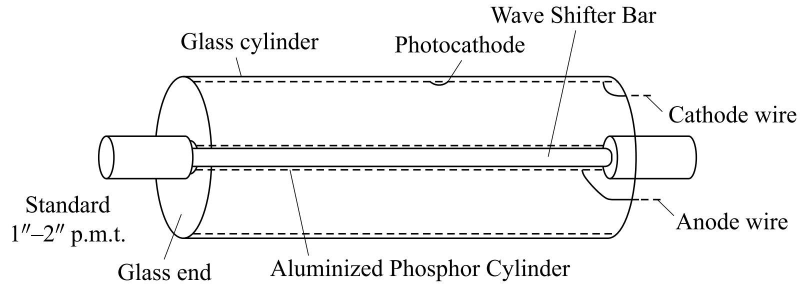
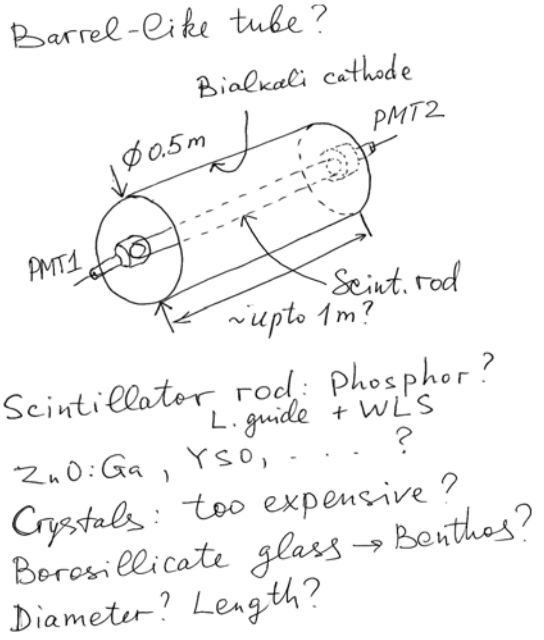


Fig. 3. Conceptual drawing of "barrel-like" hybrid phototube proposed by D. Winn [28]

inner surface of the cylinder high sensitive photocathode is deposited. Along the cylinder's axis a scintillator rod is fixed. The scintillator rod is a wavelength shifting rod covered by a fast and efficient phosphor like ZnO : Ga. Both ends of the cylinder are sealed with glass discs with special interface for the scintillator rod for detecting scintillation pulses produced by ~40 keV photoelectrons by small conventional photomultipliers. It was presumed that accelerating voltage between cylindrical photocathode and scintillator rod should be ~40 kV. There were no serious technical problems to implement such a phototube even in the



Scintillator rod: Phosphor?
L. guide + WLS
ZnO:Ga, YSO, . . . ?
Crystals: too expensive?
Borosillicate glass → Benthos?
Diameter? Length?

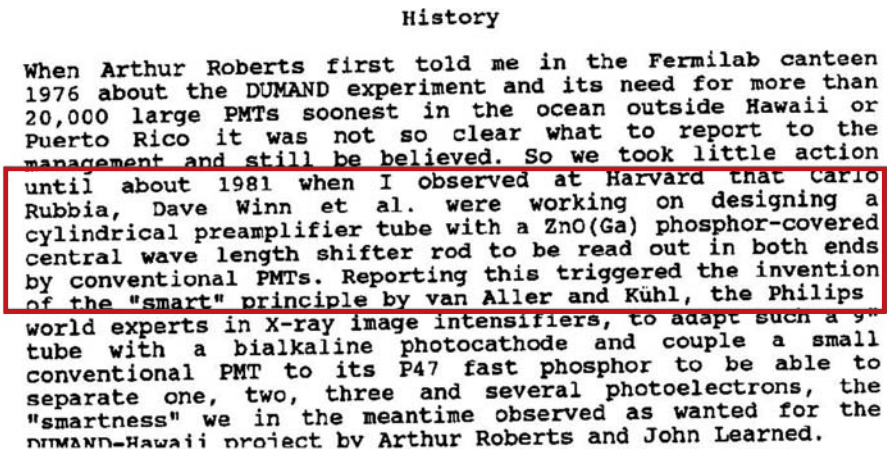
Fig. 4. A copy of transparency drawn at the meeting with Prof. Okada and Hamamatsu team (my personal archive (*B.L.*))

1980s–1990s. I recall a meeting in 1995 with Prof. Okada from ICRR of Tokyo University and discussion with Hamamatsu specialists about feasibility of the phototube manufacturing. A copy of a transparency made at the discussions is demonstrated in Fig. 4. But unfortunately, the idea was not fulfilled at that time for reasons once again "unknown" to us.

After introduction to the idea of barrel-like photodetector at Philips Laboratory, experts on X-ray image intensifiers G. van Allen, P. Kuhl, and S.-O. Flyckt started experimenting with a middle-size X-ray image intensifier equipped with fast efficient P47 phosphor ($Y_2SiO_5:Ce$) as a pilot sample. Even the first results were very promising [29]. A copy of personal reminiscences of S.-O. Flyckt, the legendary man in photon detection field, on the invention of barrel-like hybrid phototubes with luminescent screens is shown in Fig. 5 [45].

In 1985 they succeeded in the development of their first hybrid phototube with luminescent screen, marked XP2600 and called "smart" phototube indicating its ability to distinguish separate photoelectron peaks [29, 30]. It has 34.5-cm hemispherical photocathode and luminescent screen made of Y_2SiO_5:Ce crystal scintillator and fixed a bit lower of the spherical part of the phototube, Fig. 6, *a*. Accelerating voltage of 25 kV is applied to the anode (luminescent screen), and the photocathode is grounded. The scintillator is viewed by small photomultiplier from nonvacuum side of the glass bulb of the phototube. As a result, one photoelectron from hemispherical photocathode produces in average 30 photoelectrons in small photomultiplier. The phototube has an excellent single photoelectron response.

Similar "smart" phototube christened Quasar-370 was developed in the Soviet Union especially for large-scale neutrino experiments in Lake Baikal. There



History

When Arthur Roberts first told me in the Fermilab canteen 1976 about the DUMAND experiment and its need for more than 20,000 large PMTs soonest in the ocean outside Hawaii or Puerto Rico it was not so clear what to report to the management and still be believed. So we took little action until about 1981 when I observed at Harvard that Carlo Rubbia, Dave Winn et al. were working on designing a cylindrical preamplifier tube with a ZnO(Ga) phosphor-covered central wave length shifter rod to be read out in both ends by conventional PMTs. Reporting this triggered the invention of the "smart" principle by van Aller and Kühl, the Philips world experts in X-ray image intensifiers, to adapt such a 9" tube with a bialkaline photocathode and couple a small conventional PMT to its P47 fast phosphor to be able to separate one, two, three and several photoelectrons, the "smartness" we in the meantime observed as wanted for the DUMAND-Hawaii project by Arthur Roberts and John Learned.

Fig. 5. A copy of Esso Flyckt's reminiscences [45]

are copious references on the design and performance of the phototube [31–33]. It was really a fantastic machine with spectacular parameters. It had large sensitive area, 37 cm in diameter, phototube with performances of excellent small

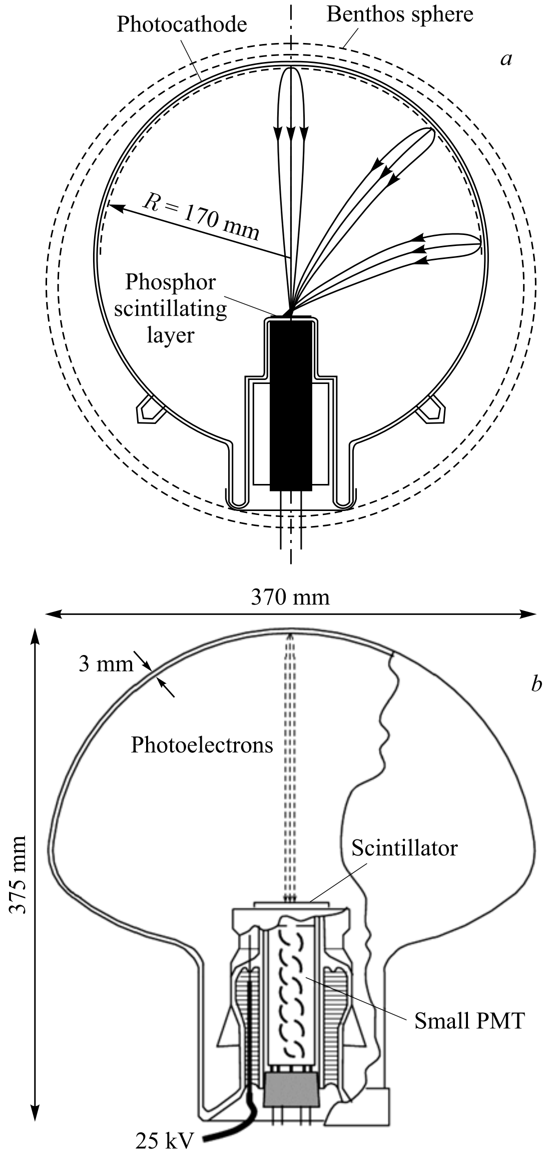


Fig. 6. Drawings of the “smart” phototubes: *a*) XP2600 [29, 30]; *b*) Quasar-370 [31–33]

photomultiplier: 1.8 ns (FWHM) jitter, 35% (FWHM) single-electron resolution, $\sim 100\%$ effective collection efficiency and immunity of its parameters to the terrestrial magnetic field. Drawings of the "smart" phototubes are shown in Fig. 6: plot *a* — XP2600; plot *b* — Quasar-370.

The idea of HPLS appeared very fruitful. In 1993 we developed a hybrid phototube christened CAMERA [34]. The phototube was developed following the idea of the first electro-optical converter proposed by G. Holst and his colleagues, the so-called "Holst glass" [21, 22]. The scheme of the CAMERA phototube is shown in Fig. 7. The phototube had continuous photocathode, continuous luminescent screen, and direct "proximity" focusing electron optics. Luminescent screen of the phototube was coupled to the matrix of APDs. At that time, silicon photomultipliers of good quality and with sensitive area more than 1 mm^2 were not available yet. Good spatial resolution of 1 mm was reached with the phototube.

The interest to such a kind of phototubes has been revived by a new approach pushed forward recently by D. Ferenc, called "Abalone" tube [35]; its conceptual drawing is presented in Fig. 8. This approach exploits the same idea of light amplification with solid state photon detectors but with a goal to reach easiness in mass production. The tube has a multi-cell design, i.e., the tube consists of many small separate cells. Each cell is in fact a smart phototube equipped with LYSO scintillator in its luminescent screen which is viewed by silicon photomultiplier glued to the scintillator. In principle, it is conceived as a pixilated phototube which can have a large sensitive area. The first pilot sample of the phototube has been successfully tested [35].

Recently a "new" idea was proposed to use a large cylinder with photocathode deposited on the inner side of the cylinder and scintillation rod on the cylinder's

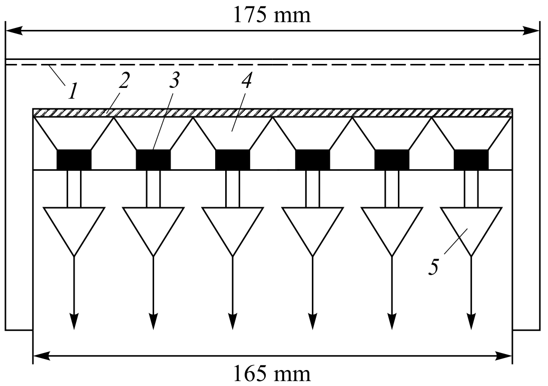


Fig. 7. CAMERA hybrid position-sensitive "smart" phototube [34]: *1* — photocathode; *2* — luminescent screen; *3* — APDs; *4* — Winston cones; *5* — preamplifiers

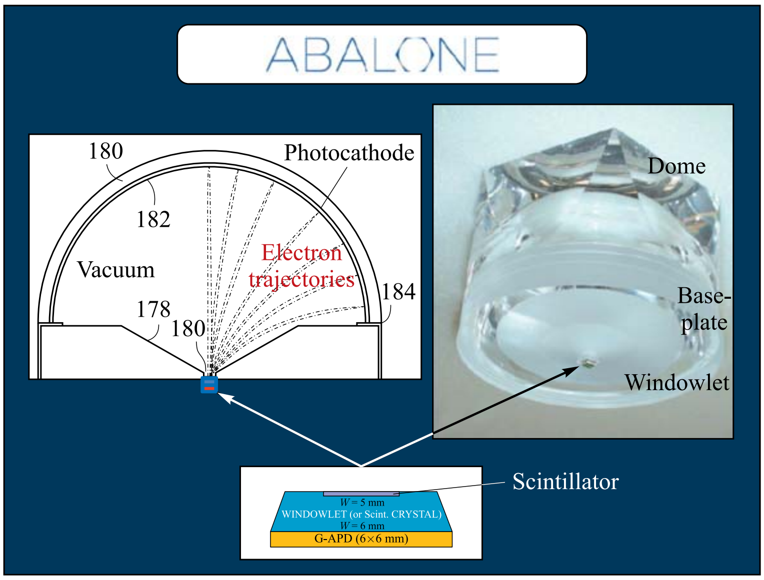
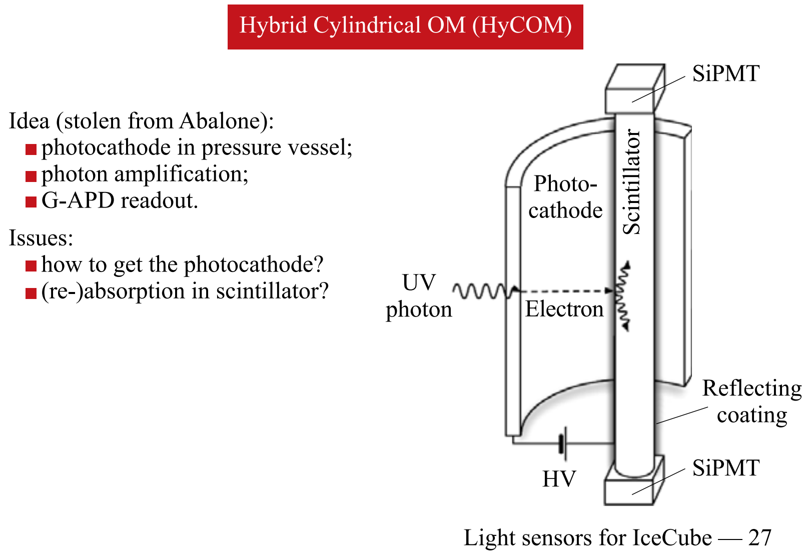


Fig. 8. Conceptual drawing of the “Abalone” phototube [35]



Hybrid Cylindrical OM (HyCOM)

Idea (stolen from Abalone):
- photocathode in pressure vessel;
- photon amplification;
- G-APD readout.

Issues:
- how to get the photocathode?
- (re-)absorption in scintillator?

Light sensors for IceCube — 27

Fig. 9. A large area hybrid phototube proposed in [36]

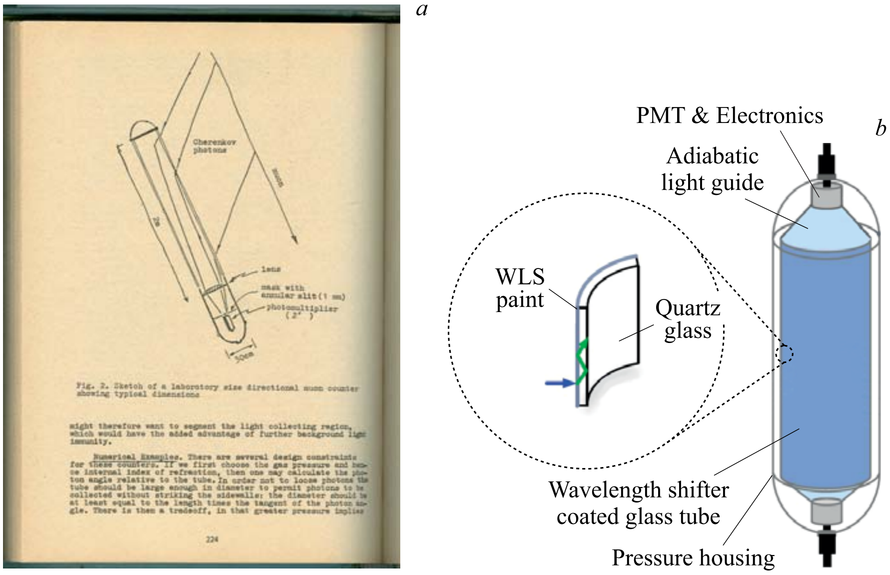


Fig. 2. Sketch of a laboratory size directional muon counter showing typical dimensions

might therefore want to segment the light collecting region, which would have the added advantage of further background lig immunity.

Numerical Examples. There are several design constraints for these counters. If we first choose the gas pressure and hence internal index of refraction, then one may calculate the photon angle relative to the tube. In order not to loose photons the tube should be large enough in diameter to permit photons to be collected without striking the sidewalls: the diameter should be at least equal to the length times the tangent of the photon angle. There is then a tradeoff, in that greater pressure implies

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Fig. 10. Large sensitive area cylindrical photodetectors. *a*) J. Learned's idea [38]; *b*) large area WLS photodetector for PINGU project [39]

axis readout out from both ends by silicon photomultiplier, Fig. 9 [36]. One can see how similar this new idea is to the old ideas of "barrel-like", "smart", and CAMERA phototubes.

The advent of new much faster and more effective scintillator materials and much more sensitive photomultipliers (vacuum and silicon photomultipliers) opens new vistas for development of new hybrid phototubes with luminescent screens with fantastic parameters [37].

In 1987, John Learned, one of the pioneers of experimental high energy neutrino physics, proposed to build large area photon detectors for deep underwater neutrino telescopes using glass cylindrical tubes, Fig. 10, *a* [38]. The idea was to trap Cherenkov light by large area light guides which would deliver the trapped photons to relatively small photomultipliers fixed at light guide caps. Very similar idea was recently proposed [39] for use in the PINGU project [40] which is presently under development in the framework of the IceCube neutrino telescope. In this case the old idea was supplemented by adding a WLS layer, Fig. 10, *b*.

Once again we see how old ideas are incarnated into the form of "new" ideas.

2. MULTI-PMTs OPTICAL MODULE

At the very beginning of the DUMAND project, there were a lot of intense discussions on photon detectors for the project. Among them there was an idea of

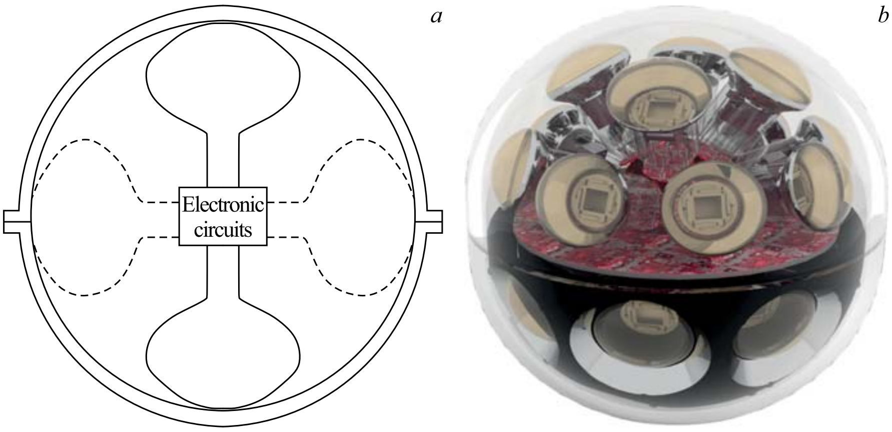

Fig. 11. Multi-PMT optical modules. *a*) Multi-PMT optical module proposed for the DUMAND project [41]. *b*) Multi-PMT optical module of KM3NeT experiment [42]

large area optical module enclosed into, let say, 17-inch Benthos sphere equipped with many relatively small size conventional PMTs [41]. At that time, the idea lost battle to large sensitive area hemispherical PMTs which had been developed for this kind of application.

Almost a quarter of a century later, in 2001, at 27th ICRC conference in Hamburg Esso Flyckt approached me with his proposal to revive that old idea. The idea has been picked up soon by KM3NeT team for their optical module design. They developed successfully the Multi-PMT optical module [42] which is considered as optical module not only for ORCA project in the Mediterranean but also for PINGU project at the South Pole. The module incorporates 36 5-inch PMTs into one 17-inch Benthos sphere, Fig. 11, *b*.

Here we witness once more the longevity of old ideas and how they evolve with time.

3. HIGH-PRESSURE PHOTODETECTORS

In deep underwater and underice large-scale neutrino experiments photodetectors should be enclosed into pressure housings to withstand high hydrostatic pressure. The pressure housings are mostly glass spheres with more than 1 cm thickness. One needs to glue photodetectors to glass spheres to provide optical contacts. Anyway, their light losses and moreover optical module preparation procedure is rather complicated business. So, an idea appeared to avoid all these problems developing high-pressure photodetector. In 1980, Hamamatsu produced such high-pressure photomultiplier with 2-inch photocathode, Fig. 12, *a* [43]. This

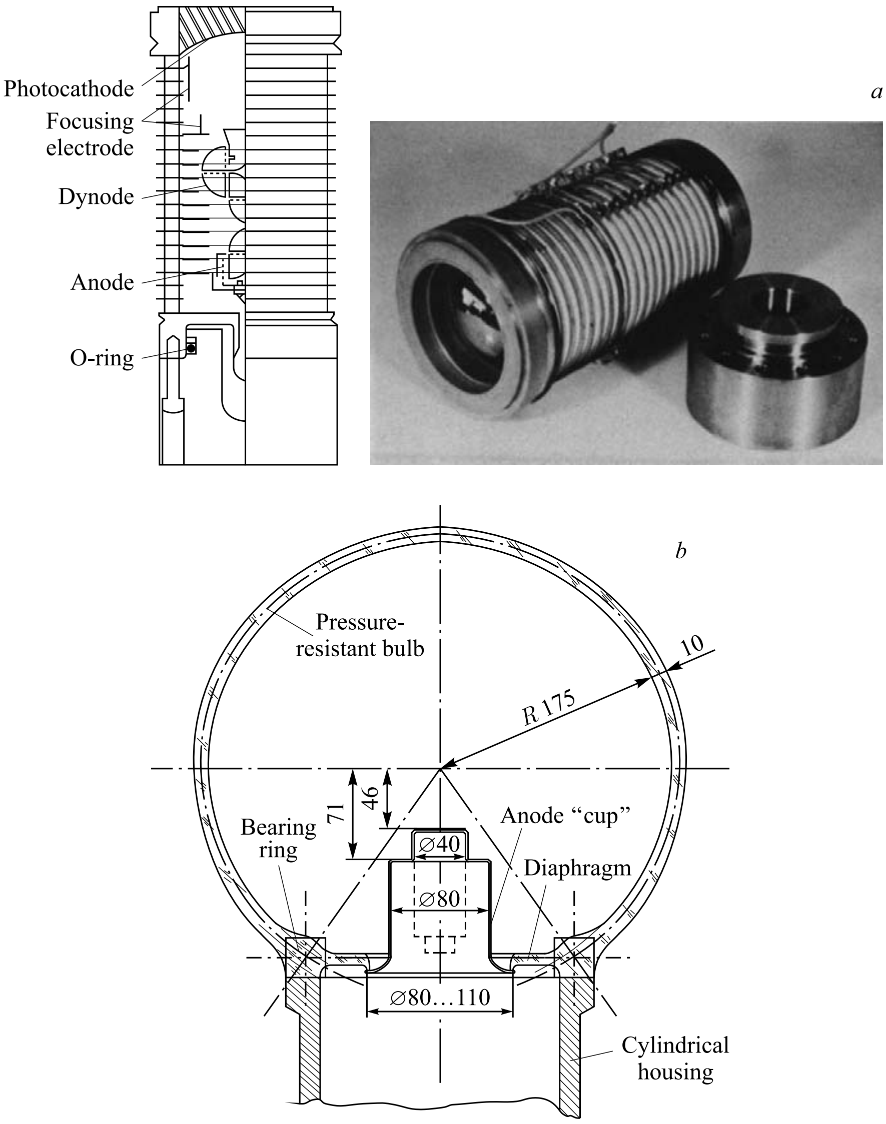

Fig. 12. Pressure-resistant photodetectors. *a*) Pressure-resistant 2-inch photomultiplier developed by Hamamatsu [43]. *b*) Pressure-resistant Quasar hybrid phototube developed at INR RAS [44]

photomultiplier could withstand 6000 m depth and could be used successfully for measurements of light background in ocean at large range of depths.

In the middle of the 1980s we were developing a large area 15-inch smart phototube [44], Fig. 12, *b*, capable to withstand at least 2000 m depth for neutrino experiments in Lake Baikal. Unfortunately, the phototube was not implemented for reasons once again “unknown” even for us.

It should be noted here that recently there are some reviving interests to this idea for several applications in large-scale astroparticle physics experiments, most surprisingly there is even an interest from large-volume liquid argon experiments.

CONCLUSIONS

I would like to quote the Old Russian proverb: “A new thing is a well-forgotten old one”. Sometimes, ideas in photon detection take very peculiar turns. Indeed, some of them are really well forgotten and rediscovered with much intellectual efforts. Working in photon detection one should look carefully back to old ideas; they are often really gold-mine of ideas which would be very useful in instigating future developments in the field.

Acknowledgements. The author is indebted very much to Dr. V. Ch. Lubsandorzhieva for careful reading of the manuscript, invaluable discussions, and many useful corrections. The work was supported by the Russian Foundation for Basic Research (Grants 13-02-9244-ASPERA-a and 13-03-12451-ofi-m).

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