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# THE PHILIPS "SMART" 15 INCH PMT

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Written contribution
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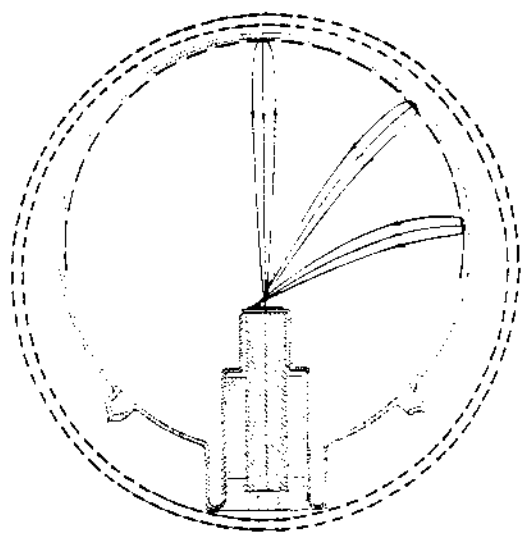

## SUMMARY

The Philips "smart" 15 inch PMT consists of the combination of an electro-optical preamplifier and a small photomultiplier tube. By accelerating the photoelectrons in the preamplifier with 25 kV towards a fast scintillator, optically coupled to a conventional small PMT, a first stage gain of more than 30 offers the "smartness" - to discriminate beween one, two, three and several photoelectrons. The tube has a maximum transit time difference of around 5 ns and is able to efficiently detect a low level signal in a high single photoelectron background environment like in the DUMAND-Hawaii experiment, with a high immunity to the earth magnetic field.
Prototype tubes have been produced and successfully tested in the DUMAND-Lake Baikal pre-experiment 1987 and the tube has now, with some delay, been completely transfered to the Philips PMT facility in France for starting the preproduction of at least 25 good tubes during 1991. The tube in its present excecution is technically satisfying the primary needs for the two approved DUMAND experiments. The patented design principle offers the possibilities of further increasing the first stage gain for increased "smartness", combined with an improved time response (jitter) and shorter scintillator decay time constant by new scintillator materials, improvements hard to reach in conventional designs.

## 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.
Backed by two working prototype tubes we patented the concept [1] and published the results at the IEEE Nuclear Science Symposium, October 1982 [2]. We quickly understood that tubes for DUMAND-Hawaii must fit inside the standard 17" pressure vessel for deep ocean work made by Benthos Inc and convinced the management to invest in adapting the tube accordingly and improve the first stage statistics by introducing a single crystal (P47) scintillator instead of the powder sedimented P47 phosphor. After some struggles with the first 6 prototypes as to high voltage (30 kV) stability, van Aller and Kühl were able to make tubes 7, 8 and 10 working as predicted, tube number 9 having an open cathode contact connection by a trivial mistake. As the X-ray image tube factory was not used to measure nanosecond pulses we engaged a physicist, Peter Bosetti from the nearby TH-Aachen to get the right "physicist" mentality in the measurement room. With some help from Mr Nussli of our PMT factory we overcame these problems and got reproducible results, nicely confirmed by the group of Kürz of KFA Jülich. April 1986 Peter Grieder of Bern was helpful in enabling us to quickly publish the results as a poster at the French-Swiss Spring Conference in Neuchâtel [3]. During the adaption phase of the tube into a spherical shape we were further strengthened in our belief in the tube by an order for two tubes from Domogatsky/Bezrukov of INR Moscow for the DUMAND-Lake Baikal project. Tubes 8 and 10 were delivered late 1986 with integrated 25 kV miniature power supplies and in the spring 1987 were used in a string placed 6 m away from a Cherenkov string telescope (3 pairs of FEU49b) triggering on downgoing muons. The main purpose was to test the response of the "smart" tube to muons passing at large distance. The results were in good agreement with theory at a depth of 475 m in the Lake Baikal and were reported at the Rochester Conference in June 1987 and fully presented in a joint paper by INR/Irkutsk/Moscow State University/Philips/Aachen at "The Caucasian Workshop on Underground Experiments" in August 1987 [4].

In the mean time we made tubes 11 - 14 with good results, found that we had a small glass tolerance problem when tube 15 did implode on the pump, and made up to tube 22 with two more tubes imploding and one having a scintillator treatment problem, the total number of good tubes being 10 out of 22 starts. We delivered 7 tubes to Peter Koske at University of Kiel, aimed at other ($^{40}K$) underwater investigations and DUMAND-Hawaii and sent one tube to Hay-Boon Mak at Queens University for SNO collaboration timing tests.
From our gathered experience we decided to modify the design slightly to avoid the glass tolerance problems and transfer it to the Philips PMT factory in France for preproduction. Backed by an order for 16 tubes for DUMAND-Lake Baikal and 7 more tubes for University of Kiel the management agreed to our plan in the summer 1989.

## The transfer to Brive, France

A multitude of books have been written on technology transfer and its inter-relation with practice - like Murphy's law.
At first everything went very well and the first tube was assembled in Brive end of 1989 including the glass redesign. However, in a transfer process many small things are made just a little different and the result was that the first tubes were noisy. We were lucky that we did not have to deliver tubes to the DUMAND-Lake Baikal as this exdperiment had decided not to deploy tubes in their spring 1990 tests in the lake.
Slowly, detail by detail the tube design and processing was corrected during the spring 1990. A project review meeting in April put a deadline to technical success or give up before November 1990. By June we had tube B8 working well but Murphy's law made a pumpstem break and the tube was later lost as were a few other tubes before tube B14 was working well and then was lost due to a trivial connection mistake. Tube B15 works well but has a slightly higher multi-electron noise than the specification, tube B16 works very well in all respects as does tube B19. In conclusion we have now passed down the learning curve of Brive and made 5 good tubes out of the 20 we had forseen it would take, although we lost 2 of them due to trivial mistakes. See table for detailed results. November 15, a management review meeting concluded that the transfer has been troublesome and costly but is now regarded as finalized and the preproduction can start with the factory commitment of producing a minimum of 25 good tubes during 1991, assuming a yield of 50%. Until now the development and transfer expenditures add up to almost one million dollars since the start of the project in 1982.

## Deliveries

As DUMAND-Lake Baikal needs three tubes in December 1990 to be able to incorporate them in their string for the spring 1991 expedition we will deliver the existing tubes to them now. For the Bosetti DUMAND-Hawaii optical module test cruise outside Rohdes with the German research ship Die Zonne, February 1991, we aim at delivering another two tubes before we start delivering Kiel and thereafter the rest of the Lake Baikal order. Due to the unification of Germany it seems now possible that the High Energy Physics Institute in Zeuthen can be funded for some tubes for the DUMAND-Lake Baikal participation to be delivered later in 1991.

## Improvements

Many measurements have been carried out on the existing prototype tubes as well in Kiel and Aachen as by Moscow State University and Univeristy of Irkutsk and by Quuens University. Frome these one can learn several things:

1. It would be good to make the preamplifier tube mushroom shaped to improve the transit time difference beween 0 and 90° from the present value of ≈ 4 ns down to ≈ 1 ns. Electron-optic simulations will start during spring 1991 but we plan to introduce such a change only when the production runs smoothly.

2. The presently used Ce-doped single crystal yttrium-silicate scintillator has been measured by Autrata et al. at the Institute of Scientific Instruments in Brno and found to have a decay time constant (1/e) of ≈ 60 ns contrary to litterature statements and measurements by INR of 35-40 ns. This makes the pulse of the 30-40 photoelectrons in the small PMT spread out and we are studying several ways of improving the time jitter that has been proven by Bezrukov to be proportional to $\tau/n_e$ where

$\tau$ = the 1/e time constant of the scintillator and

$n_e$ = the number of photoelectrons in the small PMT for single electrons in the preamplifier tube [5].

One way is to increase $n_e$ by a better optical arrangement of how the scintillator light is reaching the photocathode of the small PMT - we know we are loosing a lot of light in the present arrangement. A second way is to increase the light output of the present scintillator by optimising the Ce doping and/or increase the preamplifier tube voltage as tried and presented at Neutrino 90 by Domogatsky et al. [6].
A third way is to try new scintillators like Ce-doped Yttrium-Aluminium Perovskite (YAP:Ce) as proposed by Autrata. His measurements indicate a decay time constant of old YAP:Ce samples of 20 - 25 ns but only half the light output of our sample of $Y_2SiO_5$:Ce [7]. Autrata will now test recently produced samples from Monokrystaly in Turnov of YAP:Ce and we will soon get results on the samples we have, in real tubes. In parallel we will order samples of YAP:Ce from a USSR source. Autrata's expectation is that by optimising YAP:Ce it should be possible to improve the light output to some 80% of the $Y_2SiO_5$:Ce with a contained decay time of 20 - 25 ns. Autrata will also make experiments to optimise the crystal shape and geometry to get more light output based on his experience in electron microscopes.

We are also awaiting confirmation from BNL decay time measurements on our sample of $Y_2SiO_5$:Ce by Derenzo et al.

It looks thus possible to obtain at least half the decay time constant with a contained first stage gain of 30 - 40 to keep the resolution of one, two, three and several photoelectrons combined with an improved time jitter.

## Readout electronics

Presently existing electronics takes the pulse shape into account of traditional PMTs as to pulse charge and timing. Peter Bosetti et al. at TH-Aachen have designed a "smart" readout electronics package specially adapted to our tube which takes as well pulse integrated charge as leading edge timing into account, thereby enabling the setting of a very low threshold to make use of the good (for such a large tube) timing characteristics and eleminating sporadic noise. This principle is presented elsewhere in this workshop.

## Long term improvements

Possible long term improvements could be to modify the tube slightly by having several or one segmented crystal as the photoelectron target and read it out with a segmented PMT in e.g. four quadrants or 4 x 4 pixels to get some directional rough imaging "smartness" as well which is in line with some wishes of University of Kiel and possibly could be of value to the DUMAND detectors as well.

## Conclusions

The Philips "smart" 15 inch PMT is by now well tested both in the laboratories and underwater. It satisfies the primary needs for the two approved DUMAND experiments.
The tube is now successfully transfered for preproduction in the Philips PMT factory in Brive, France. During 1991 some improvements will be introduced as to scintillator material. Studies will start on improving the timing through a more optimal preamplifier tube shape and maybe a higher bias voltage. The tube principle offers further possibilities to introduce rough imaging ideas for some directional response, improvements hard to reach in conventional PMT designs.

TABEL

| TUBE | SE noise > 0.5 PE [cps] | ME noise >2.5 PE [cps] | >4 PE [cps] | Gain | $S_k$ [μA/lmF] |
|---|---|---|---|---|---|
| B008 | 23,500 | NM | 275 | 35 | NM |
| B014 | 38,000 | 2100 | NM | 31 | 9.0 |
| B015 | 30,000 | 2000 | 1300 | 36 | 10.5 |
| B016 | 10,000 | 910 | 690 | 40 | 9.5 |
| B019 | 11,700 | 200 | 95 | 35 | 9.1 |

Legend: SE = Single electron noise, threshold >0.5 PE
ME = Multi-electron noise, threshold >2.5 PE & >4 PE
$S_k$ = Photocathode sensitivity for blue light with a filter Corning CS 5-58, half stock thickness expressed in μA/lmF , F= filtered.
NM = Not measured.

Tubes B008 and B014 are lost by trivial mistakes.

## References

[1] Netherlands Patent 8202546, Jun. 23, 1982 and United States Patent 4,564,753, Jan. 14, 1986 and patents in many other countries.

[2] G. van Aller, S-O Flyckt, W. Kühl, IEEE Trans. Nucl. Sci.,NS-30, 469(1983).

[3] G. van Aller, S-O Flyckt, W. Kühl, P. Linders and P. Bosetti, Helvetica Phys. Acta. 1986. Vol.59.

[4] L.B. Bezrukov et al. Proceedings from "The Caucasian Workshop of Underground Experiments, August 1987.

[5] Private communication with L.B. Bezrukov at Neutrino 90.

[6] G.V. Domogatsky et al. Presentation of the Lake Baikal project at Neutrino 90, Cern, Geneva, June 1990.

[7] Private correspondence with R. Autrata, Institute of Scientific Instruments, Brno, Czechoslovak Academy of Sciences, October 1990.