Vacuum Silicon PhotoMultiplier Tube: prototypes and engineering

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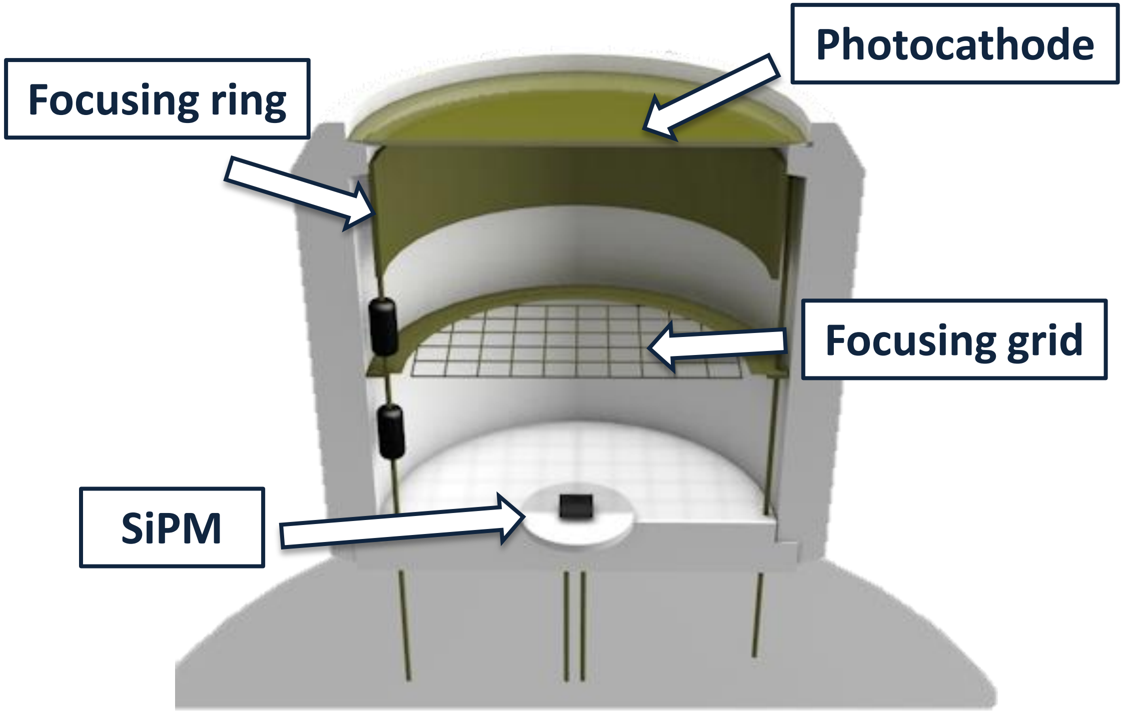
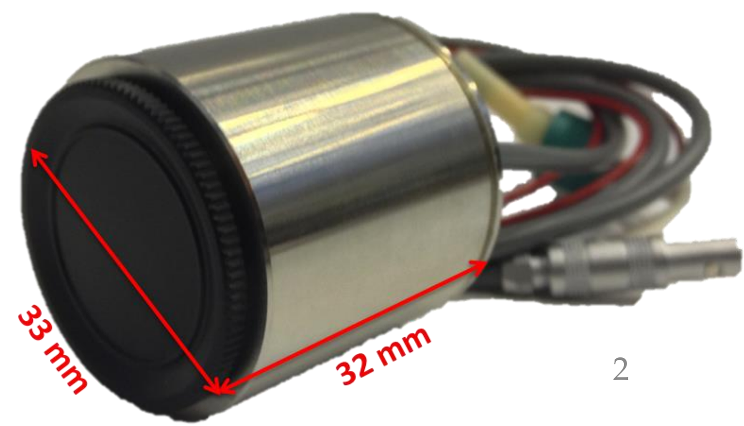
Vacuum Silicon PhotoMultiplier Tube
VSiPMT



Two prototypes by Hamamatsu Photonics

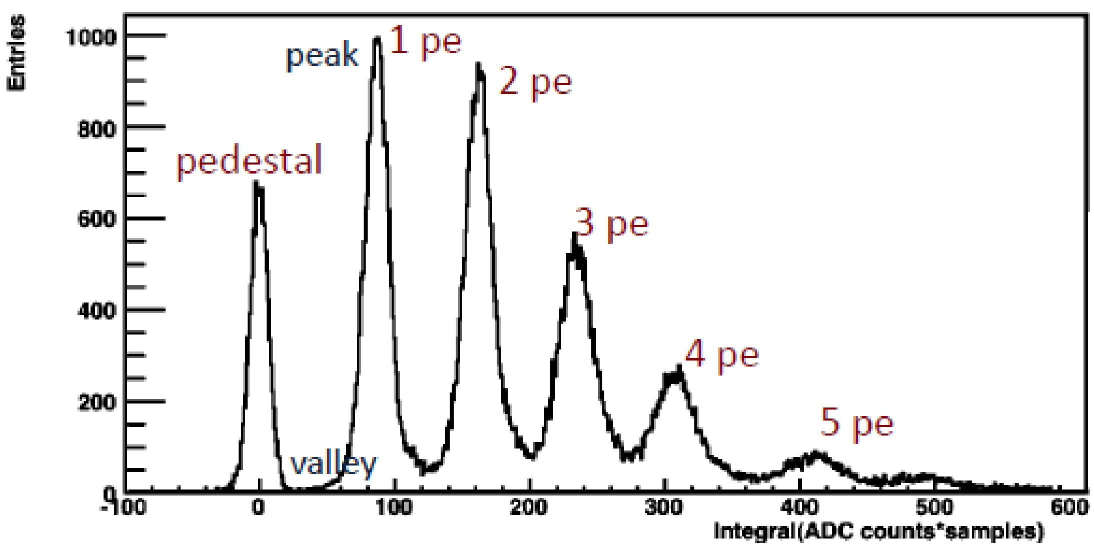
- $7x7$ mm^2 Borosilicate glass entrance window
- 3 mm Ø GaAsP photocathode
- $p^+n\nu n^+$ configuration
- special non-windowed MPPC series

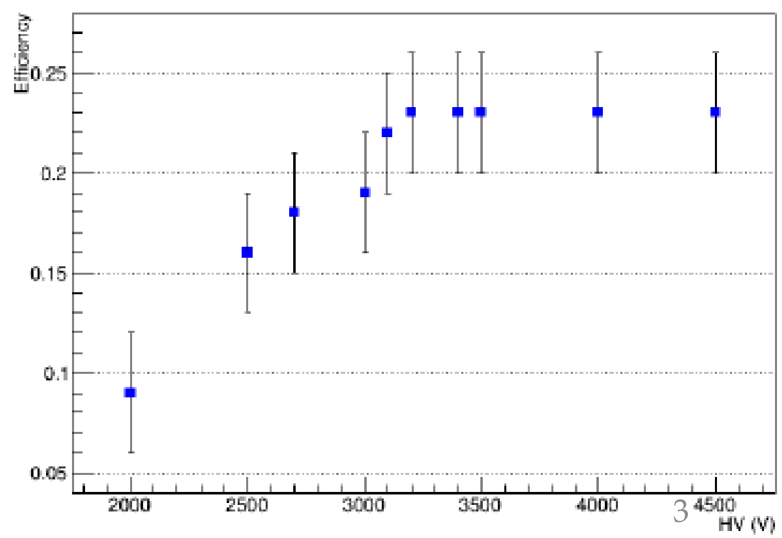
Prototype	ZJ5025	ZJ4991
SiPM Area (mm^2)	1×1	1×1
Cell size (μm)	50	100
Total number of cells	400	100
Fill Factor	61%	78%



VSiPMT features

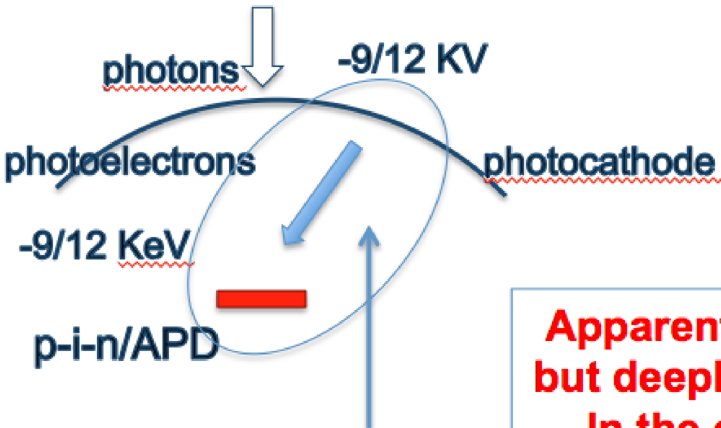
- Excellent **photon counting** capabilities
- Photon Detection Efficiency: **≈23%** @ 407nm
- High gain: **$10^5 \div 10^6$**, HV-stable
- Good timing performances: **TTS < 0.5ns**
- Low power consumption: **5mW** (amplifier stage)
- SPE resolution **17.8%**
- Peak-to-valley ratio **≈65**



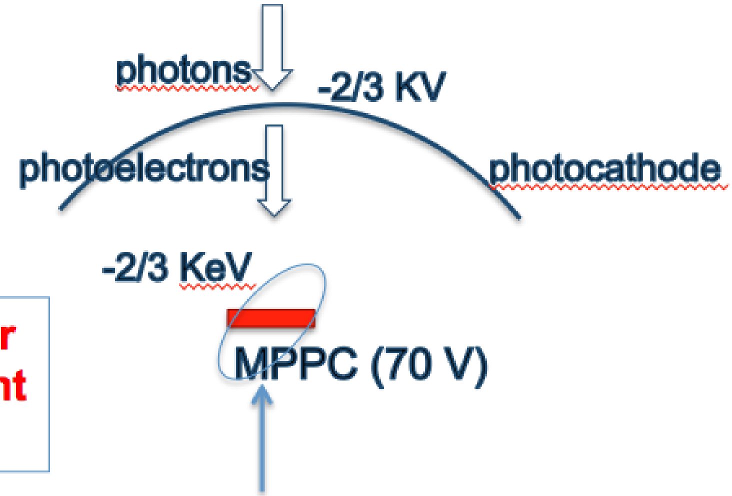


VSiPMT vs HAPD

HAPD



VSiPMT



Apparently similar but deeply different In the concept

Need of HV to obtain a high gain

High gain obtained with low voltage in the SiPM

Drawbacks of the APD solution

- **$G=E_{phe}/E_{e,h}\approx 10^4\text{-}10^5$**
- too **low Gain. HV gain required**
- G **depending** on HV
- Need a strong HV critical **stabilization.**
- Difficult **and expensive insulation**

Advantages in the VSiPMT solution

- **$G > 10^6$** : a factor 10 higher.
- **Low HV, no need for bombardment gain** only energy for photoelectron transfer
- **Low voltage Gain: easy to stabilize**
- **Normal insulation**

VSiPMT vs PMT

	PMT	VSiPMT	comparison
Efficiency	Photocathode x 1st dynode	Photocathode x Fill factor MPPC (➔1)	**≈ comparable (slightly worse)**
Gain	10^6 - 10^7	≈ 10^6	**≈ equivalent**
Timing	nsec	fractions of nsec (no spread dynodes)	**+ VSiPMT**
Power Consumption	Divider Dissipation	No dissipation: just amp. G=10-20 (<5mW)	**+VSiPMT**
Stability H.V.	H.V. stabilization for stable gain	No H.V. stability (plateau)	**+VSiPMT**
Dark counts	≈ kHz @ 0.5pe	≈100 kHz/mm^2 @0.5pe	**+PMT**
Photon counting	difficult	excellent	**+VSiPMT**
Linearity	depending on gain	depending on focusing	**≈+PMT**
Peak-to-valley	≈ 3 (typ.)	> 60	**+VSiPMT**
Afterpulse(@0.5pe)	≈ 10%	Next gen. MPPC <0.3%	**+VSiPMT**
SPE resolution	≈ 30% (typ.)	≈ 17.8%	**+VSiPMT**

Feasibility study of a 3'' VSiPMT

VSiPMT prototypes characterization provided the unequivocal proof of feasibility of the device.

New prototypes are currently under study

Constraints

- Physics applications require significantly bigger sensitive areas;
- Keep power consumption and TTS as low as possible;
- Linearity must be improved.

Engineering and design phase

- development of two VSiPMT prototypes (1 inch and 3 inches photocathode area, respectively);
- focusing system for linearity and TTS optimization;
- Silicon layers structure for efficiency maximization.

3-inch VSiPMT: Photocathode

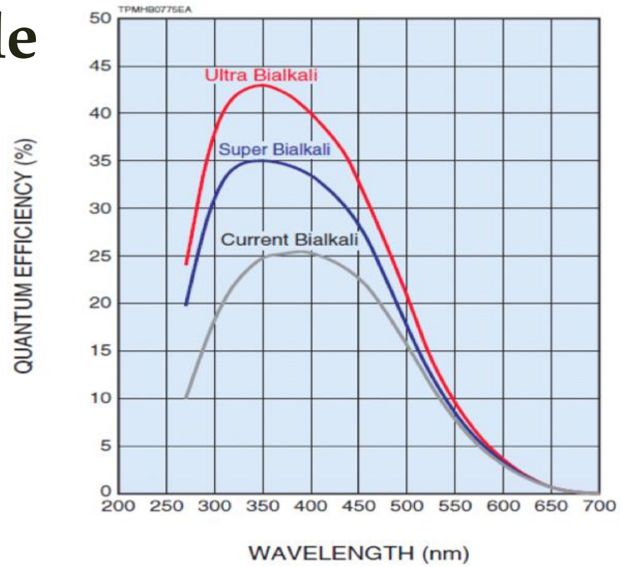
In use: **GaAsP transmission mode photocathode**

Performances
- wide band gap, covering all the visible wavelengths
- high quantum efficiency (up to ~50%)

Drawback
realizable only by **epitaxial growth** in flat shape → high manufacture complexity and costs

Feasible solution: **Ultra Bialkali transmission mode photocathode**

Performances
- spectral response ranging between 300 nm and 600 nm
- low noise
- realized by **evaporation**: large surfaces and curve shapes, lower costs

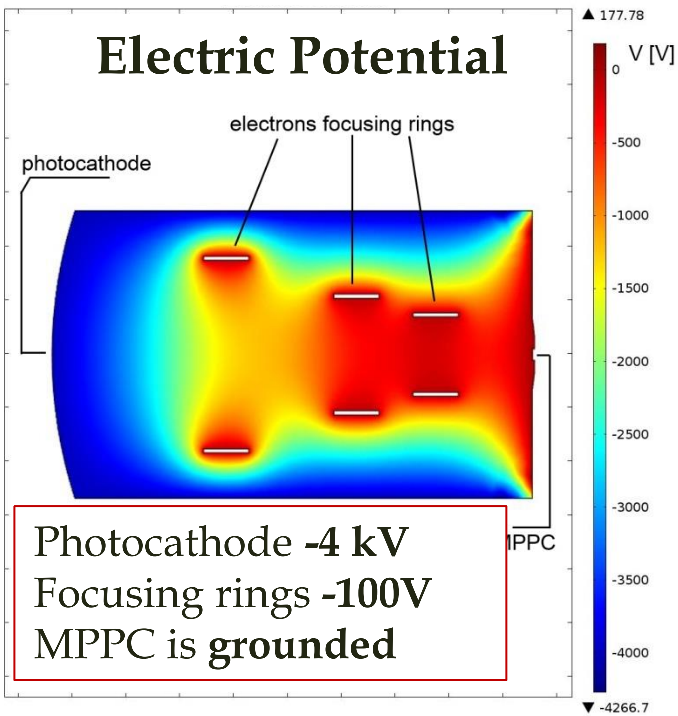


3-inch VSiPMT: Focusing

A too **strong focusing** means that not all pixels are involved → **drastical reduction of the linearity**

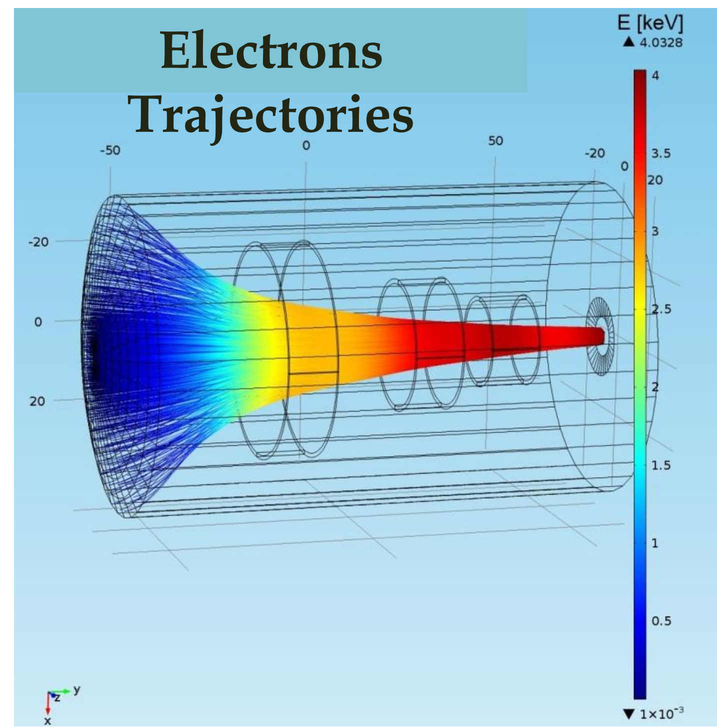
A too **weak focusing** means that a fraction of the pe misses the target → **decrease of the overall PDE**

Proposed Solution

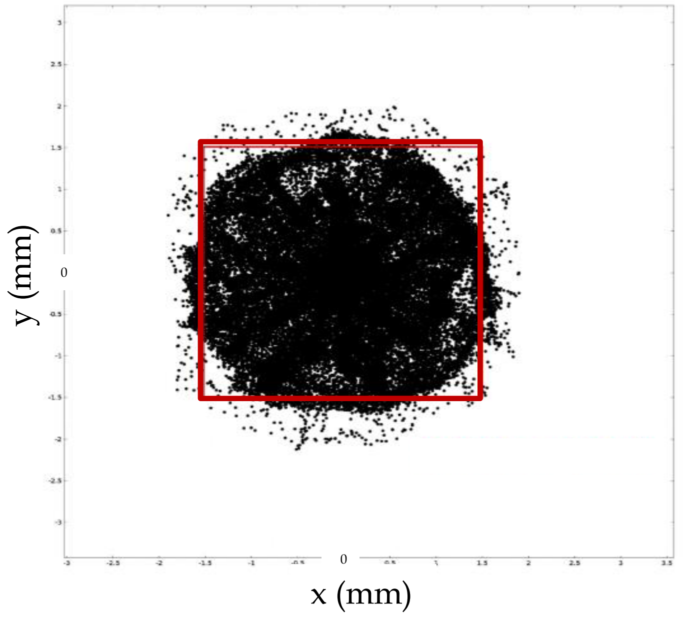


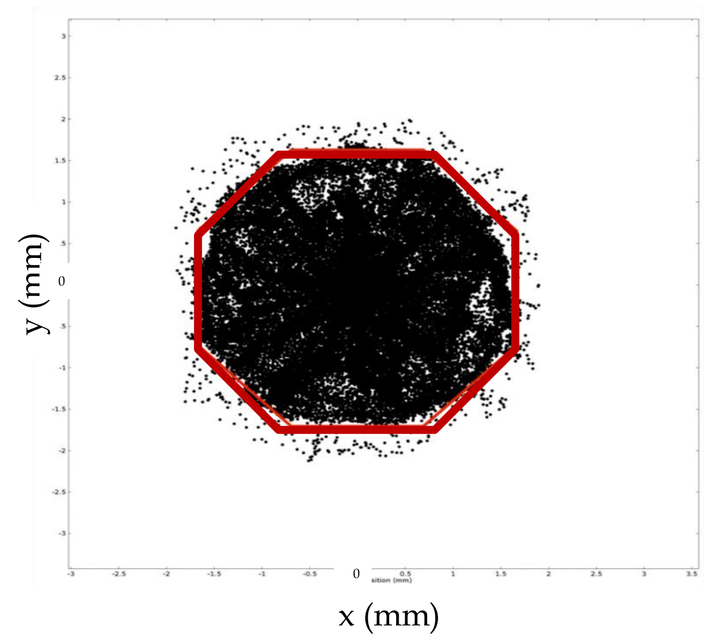
Photocathode **-4 kV**
Focusing rings **-100V**
MPPC is **grounded**

Three focusing rings:
- **first focusing ring** for time alignment of all electrons paths
- **second** and **third focusing rings:** fine tuning of the electron beam focusing



3-inch VSiPMT: SiPM shape



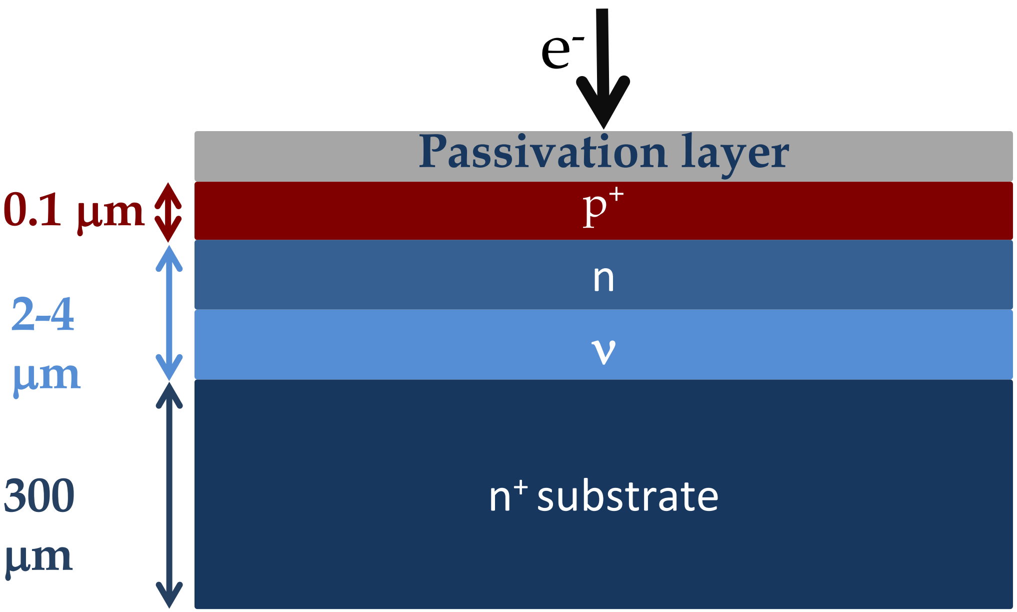


To adapt the sensitive area of the electron multiplier to the shape and to the size of the pe spot and reduce dark counts:

- **Octagonal-shaped**
- **Standard square with “blind” corners**

3-inch VSiPMT: SiPM structure

SiPM currently in use: blue/UV-enhanced
- depletion region close to surface
- p-on-n structure for e^- detection optimization



Passivation layer: ~100 -150 nm of **SiO_2**
- excellent transmission of light
- protection from environmental factors

reduction of the photocathode HV

↓

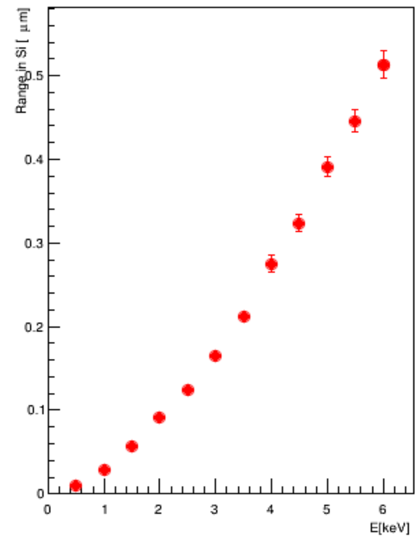
investigation of alternative solutions based on a **thinner SiO_2 passivation layer**

3-inch VSiPMT: SiPM structure

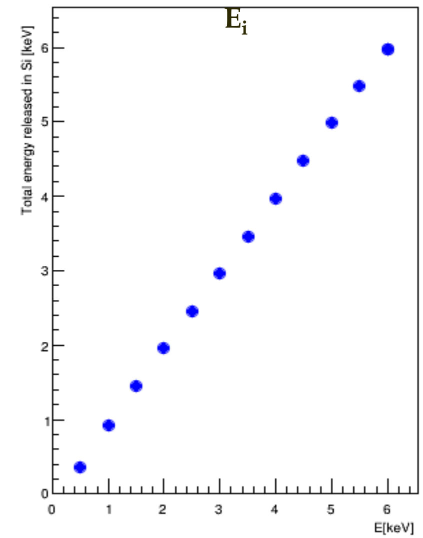
Geant4-based simulation

Geant4-MicroElec extension for low energy processes in Silicon included in *Geant4 10.0 Release*

RANGE in Si vs E_i



Total E deposit in Si vs E_i



4 nm passivation layer

Passivation layer	Energy threshold (E_{th})	Total energy deposit in Si @ E_{th}
150 nm	4 keV	~1.8 keV
100 nm	**3.5 keV**	**~2.2 keV**
50 nm	3 keV	~2.6 keV
15 nm	2.5 keV	~2.3 keV
4 nm	**>2 keV**	**~2 keV**

4 nm SiO_2 passivation layer: the energy threshold for e^- drops to **2 keV** ➔ reduction factor of 2 with respect to the first generation prototypes

Application of the VSiPMT to Water Cherenkov detectors

- Much easier-to-stabilize gain
- Highly reduced power consumption

↓

Advantages in detector construction and maintenance

- Lower TTS (factor > 3)
- Improved Peak-to-valley ratio (factor >20)
- Excellent photon counting capabilities

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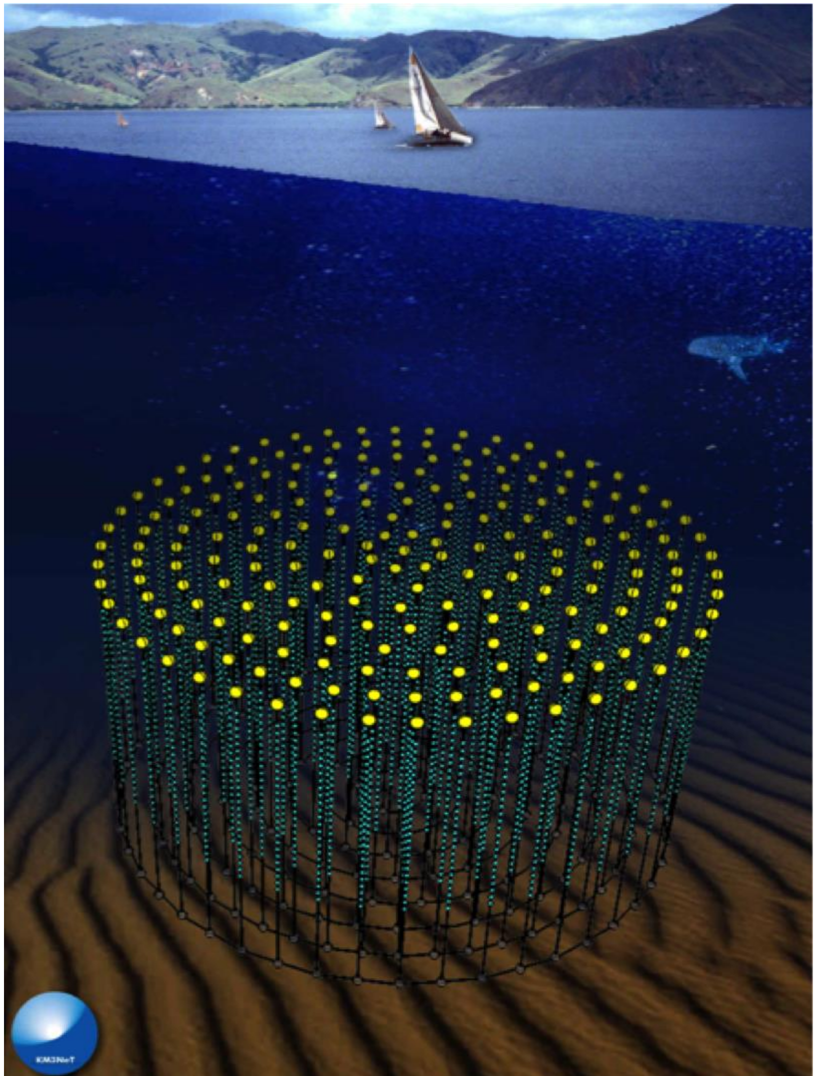
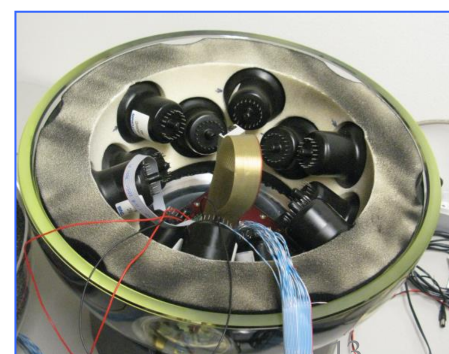
Improvements in reconstruction quality

An attractive solution for Water Cherenkov experiments



Km3NeT experiment

- Multi-site 3-D array of optical detectors
- km^3 volume
- deep sea infrastructure
- Digital Optical Modules
- 31 PMTs each

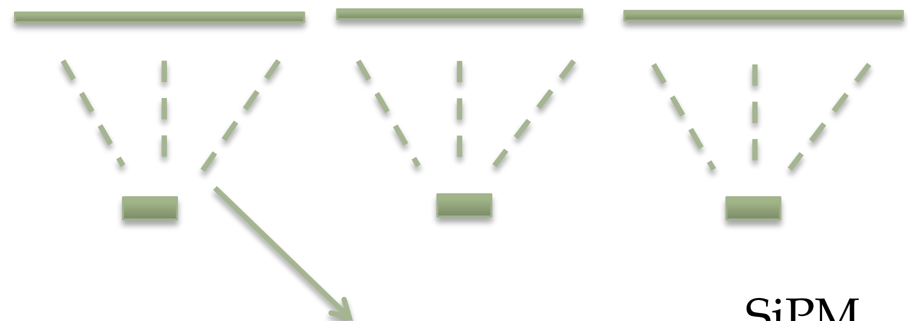


…and for applications in HK

DOM structure as in Km3Net

Use 3′′ VSiPMT

High granularity for background rejection and improvement of reconstruction quality



Next step:

WC detector simulation based on WCSim

- semi-DOM with 3′′ PMT
- semi-DOM with VSiPMT
- flat photocathode surface VSiPMT

Conclusions and Perspectives

VSiPMT is an innovative design for a modern hybrid photodetector based on the combination of a Silicon PhotoMultiplier (SiPM) with a Vacuum PMT standard envelope

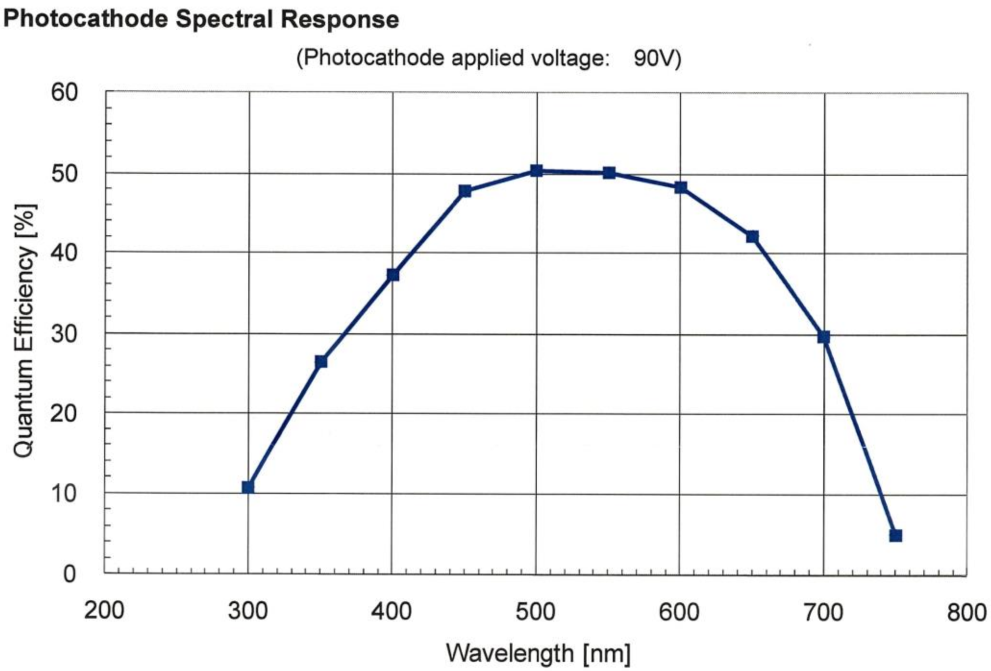
Unprecedented features:

- Photon counting capability;
- Low power consumption;
- Large sensitive surface;
- Excellent timing performances (low TTS);
- High stability (not depending on HV).

- Engineering and design phase: Naples INFN group studies towards a 3′′ VSiPMT prototypes
- Collaboration with Hamamatsu for new VSiPMT prototypes
- Simulation studies towards a VSiPMT application in WC detectors in HK

Engineering: photocathode/1

In use: GaAsP transmission mode photocathode



Excellent performances

- wide band gap, covering all the visible wavelengths
- high quantum efficiency (up to ~ 50%).

Drawback

GaAsP photocathodes can be made only by epitaxial growth

➔ realizable only in flat shape, with high manufacture complexity and costs.

Only for small size devices

Engineering: photocathode/2

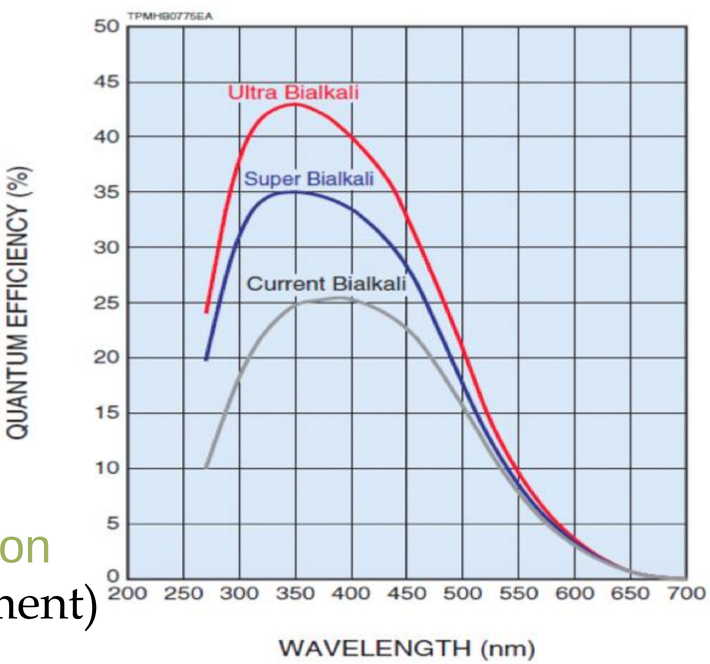
Feasible solution: bialkali transmission mode photocathode

Pros

- typical spectral response ranging between 300 nm and 600 nm;
- low noise;
- realized by evaporation. Therefore, large surfaces and curve shapes are easily obtainable with much lower costs wrt GaAsP (about one order of magnitude).

Warning

- significantly lower QE wrt GaAsP
- visible band not completely covered



enhanced bialkali photocathodes generation
(crystallinity of the antimony film improvement)

Engineering: focusing/1

Weak focusing

the photoelectron spot exceeds the size of the G-APD

➔ a fraction of the ps misses the target and is systematically lost

➔ the overall PDE of the device decreases.

Strong focusing

too much squeezed photoelectron beam

➔the photoelectron spot intercepts only a fraction of the active surface of the G-APD

➔the linearity of the device is reduced.

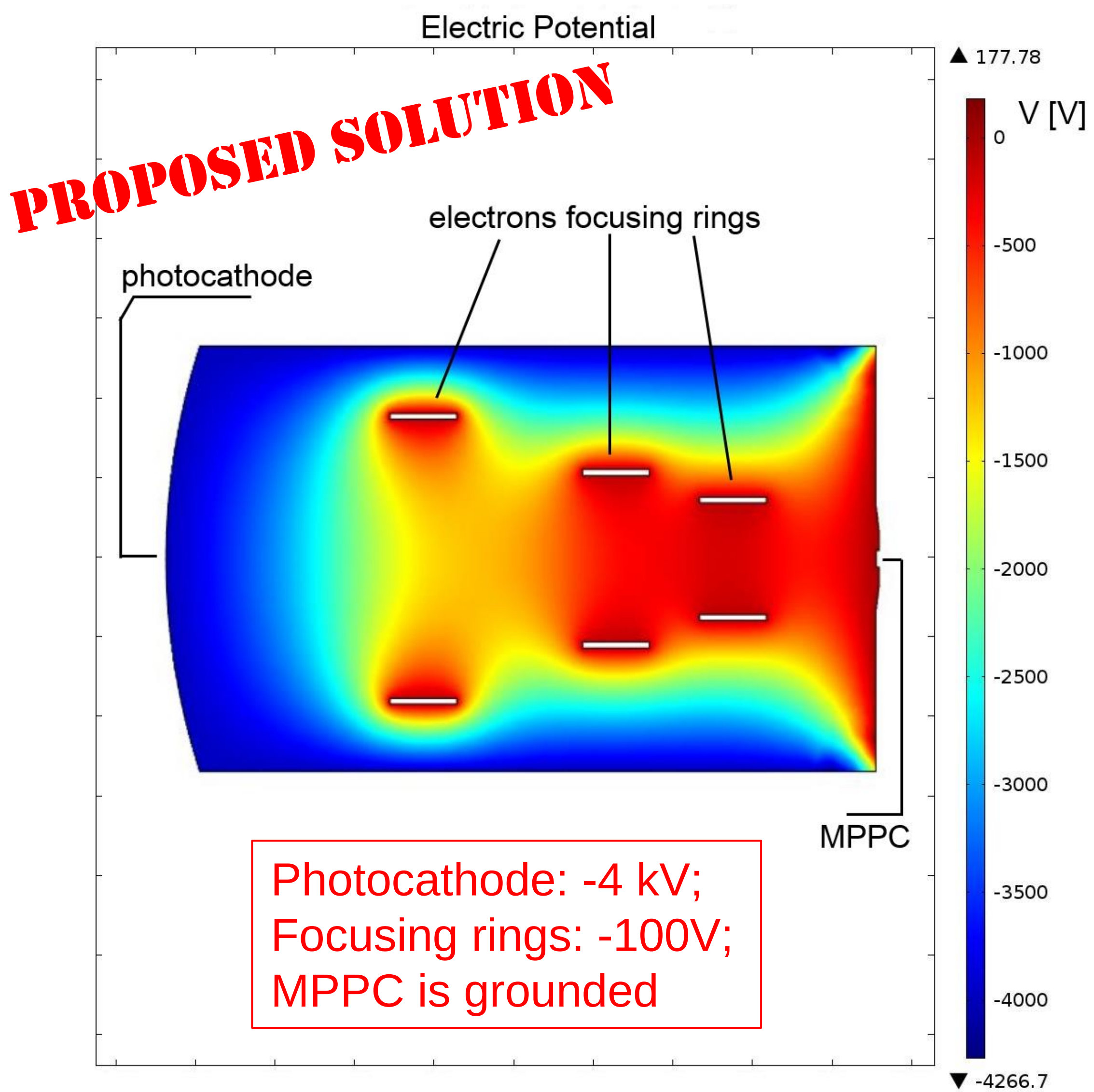
OPTIMAL SOLUTION

electrostatic focusing system generating a photoelectron beam with the same size of the G-APD

Additional drawback

all the G-APD pixels not involved in the electron multiplication process are still dark noise sources.

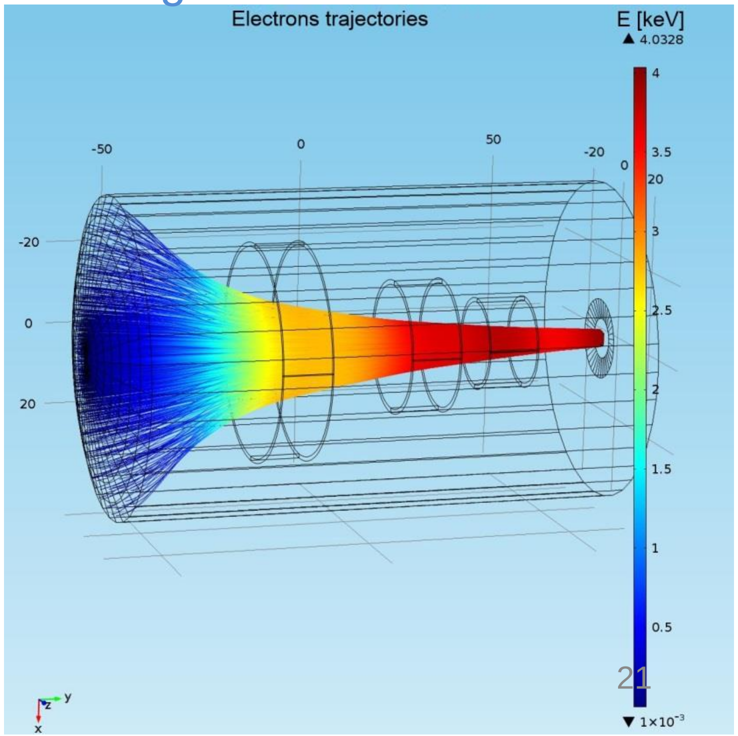
Engineering: focusing/2



Photocathode: -4 kV;
Focusing rings: -100V;
MPPC is grounded

First focusing ring: time alignment of all possible electrons paths;

Second and third focusing rings: fine tuning of the electron beam focusing



Engineering: SiPM

New generation of Hamamatsu MPPCs:

- sensibly lower afterpulse rates (≈10% ➔ < 0.3%);
- lower noise: much reduced dark counts (about one order of magnitude);
- higher gain ➔ no amplification required (persp.), still lower power consumption;
- higher fill factor ➔ higher dynamic range keeping a good PDE, improved linearity.

Shape optimization for dark noise reduction

- Octagonal-shaped G-APD: to adapt the sensitive area of the electron multiplier to the shape and to the size of the pe spot;
- standard square G-APD with "blind" corners: all the pixels that are not involved in the electron multiplication process are turned off.