Westfälische
Wilhelms-Universität
Münster

Multi-PMT Optical Modules

for application in harsh and remote environments

HAP Workshop: Advanced Technologies
University of Mainz, 2. Feb. 2016

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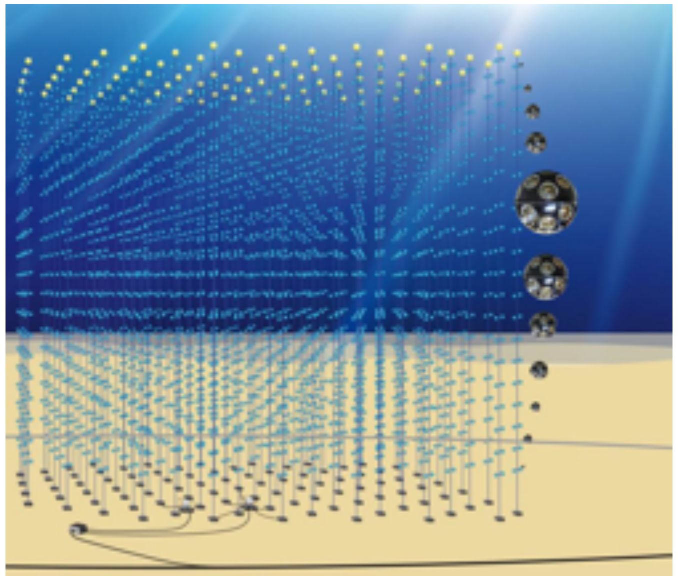
Institut für Kernphysik

Target applications

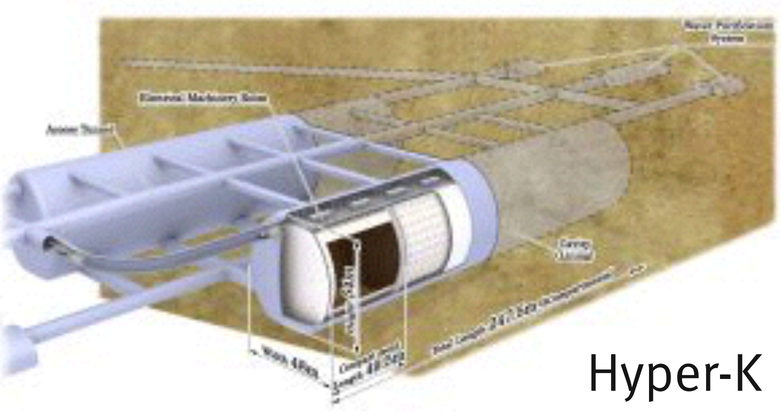
Detection of Cherenkov radiation of charged particles

Examples of target experiments

- Neutrino telescopes (IceCube, KM3NeT, BAIKAL)
  - high-energy astrophysics
  - MeV supernova neutrinos
  - neutrino oscillation at GeV energies (oscillation parameters, mass ordering)
- Large-volume-tank detectors (e.g. Hyper-K)
  - neutrino oscillations in sub-GeV to GeV range (CP phase, mass ordering)
  - MeV supernova neutrinos, solar neutrinos
  - proton decay
- Neutrino detectors in lakes (CHIPS)
  - CP phase in neutrino oscillations



KM3NeT (artist's view)

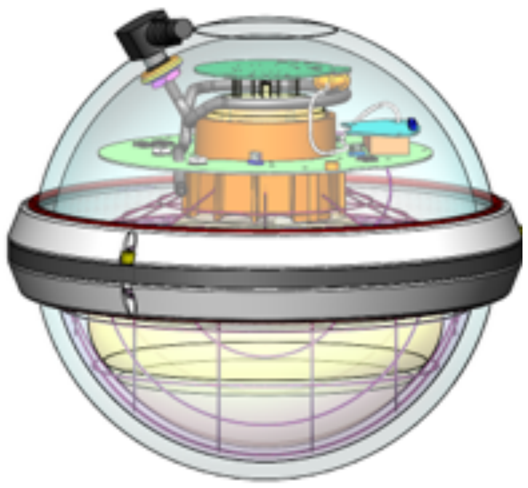


Hyper-K

Desired properties of optical modules

- Large effective area
- Single photon detection and high dynamic range (› several 100 p.e.)
- Good photon separation (photon counting)
- ns timing
- Low background
- Directional information (with 4π sensitivity)
- 10+ years of maintenance-free operation under (and/or)
  - high pressure (up to 600 bar),
  - low temperatures (-45°C),
  - corrosive environments (salt water)
- Low power consumption (few Watts)
- Cheap (« 10 kEUR)

Optical modules in neutrino telescopes

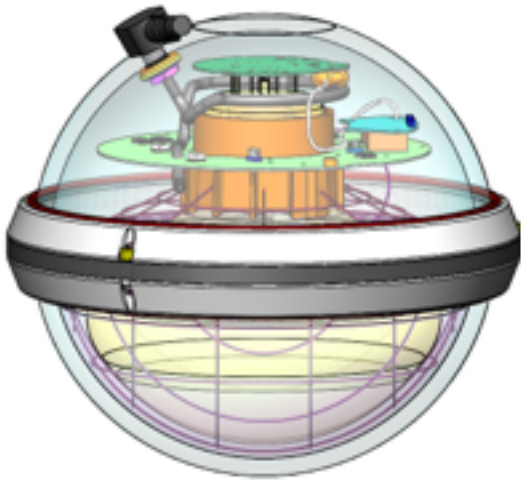


IceCube Optical Module

Until recently, single large PMT in glass sphere looking downwards (DUMAND, BAIKAL, AMANDA, ANTARES, IceCube)

- Advantageous features
  - in particular sensitive to up-going neutrinos (main target in the beginning)
  - only one readout channel (electronics complexity)
  - price per photocathode area used to be lower for large PMTs
- Disadvantages
  - no directional sensitivity (direction reconstruction)
  - $\ll$ 0.5 of solid angle covered (sensitivity to down-going ν)
  - ambiguities in photon counting (energy determination)
  - no local coincidences on single module (e.g. for background suppression)

Optical modules in neutrino telescopes



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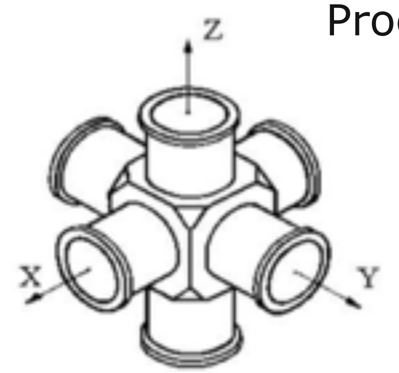
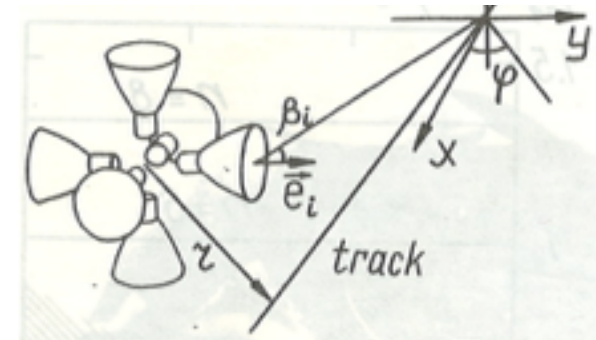
→ multi-PMT optical modules aim at improving on these

Multi-PMT optical modules



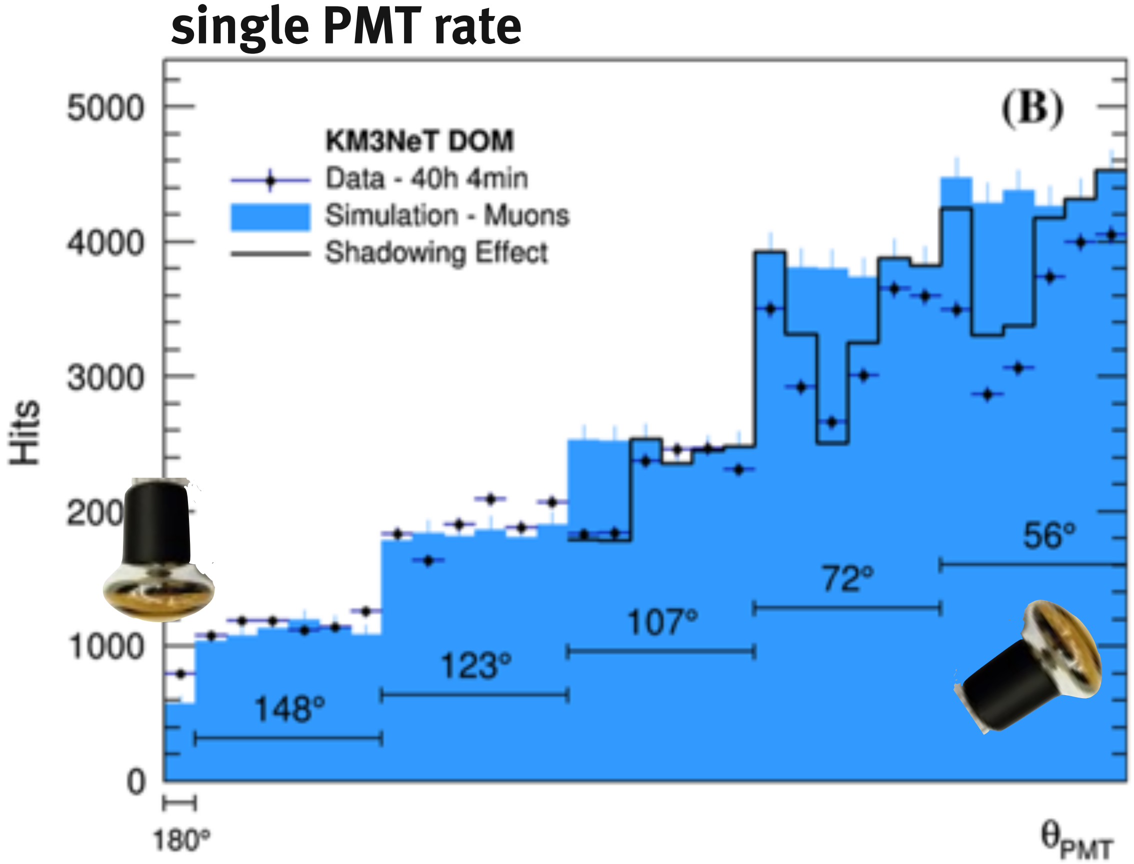
NEVOD module

Borog et al,
Proc. DUMAND Workshop 1979

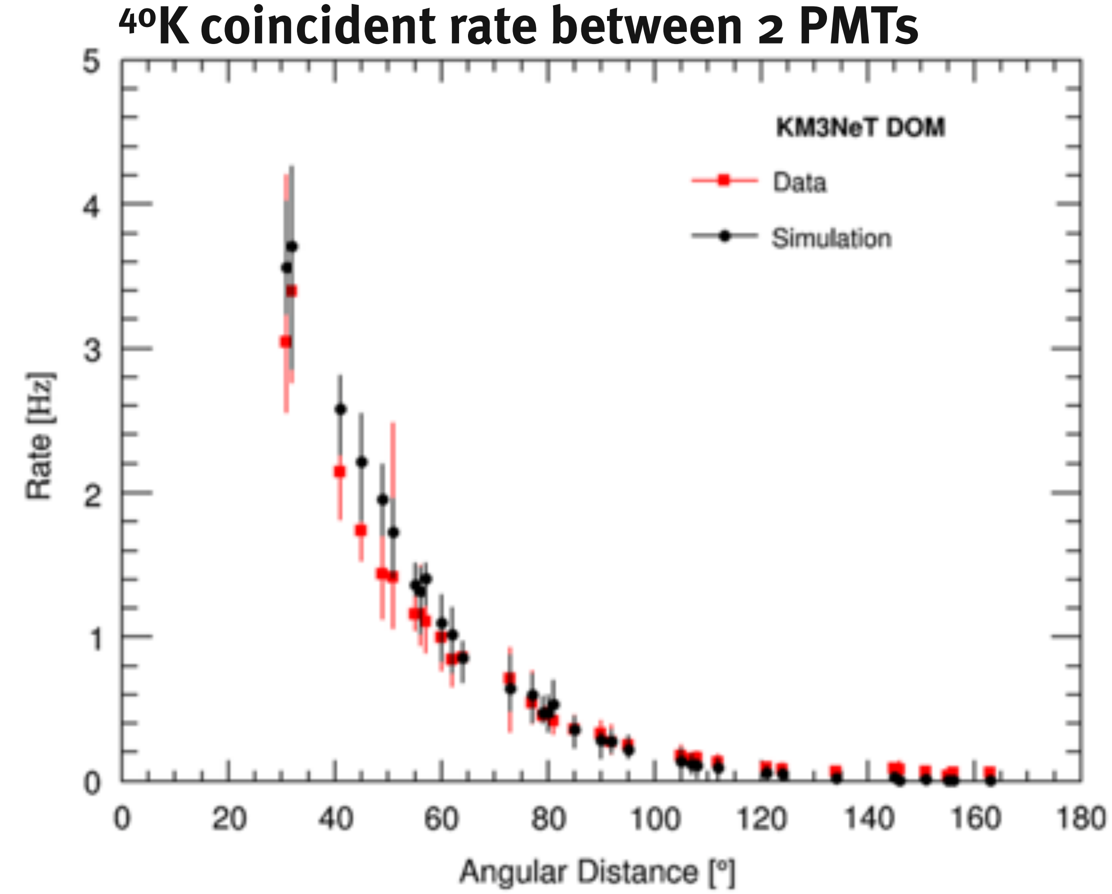


- Already thought of in the DUMAND era (1979) and realized in NEVOD!
- First "modern" version in KM3NeT (Kavatsyuk et al, NIM A 695 (2012))
  - PMTs still best choice for low background applications
  - today, price per photocathode area for 3" PMTs < 10" PMTs (in mass production)
  - advances in electronics / data transmission
- Successful in-situ application in KM3NeT

Borog et al.



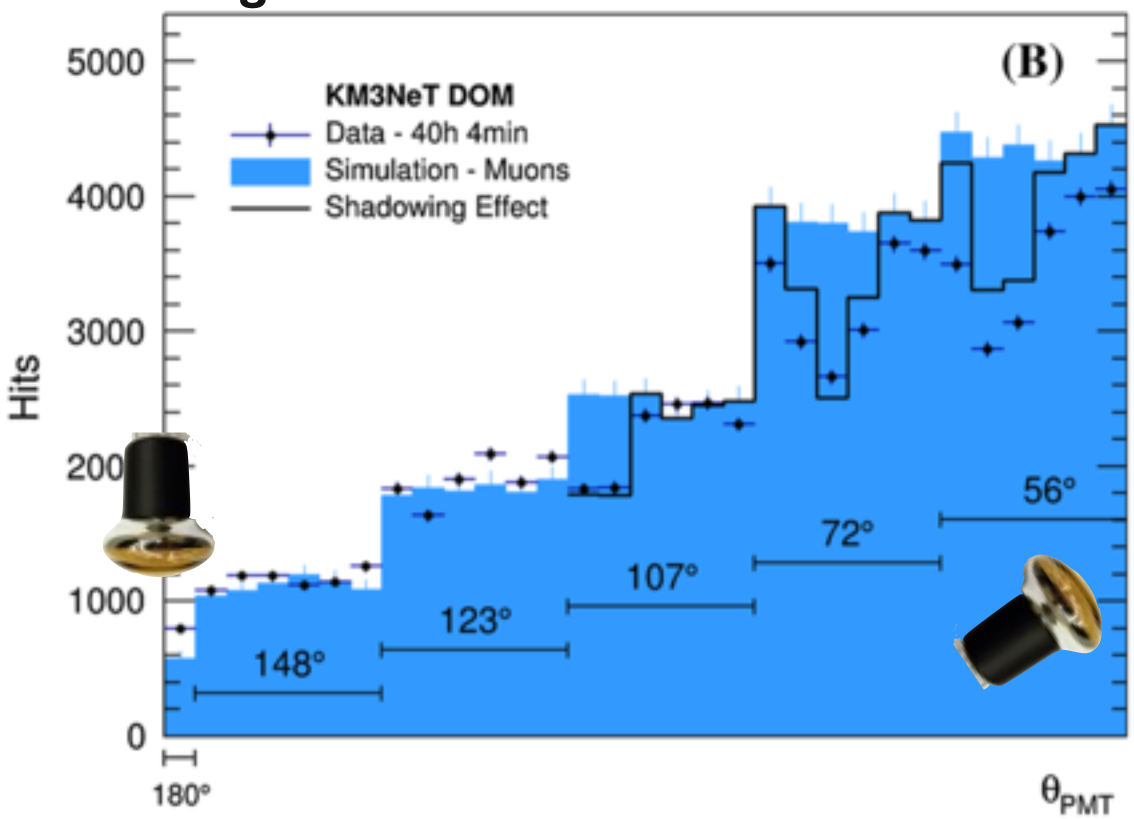
KM3NeT, Eur. Phys. J. C (2014)



- Successful in-situ application in KM3NeT

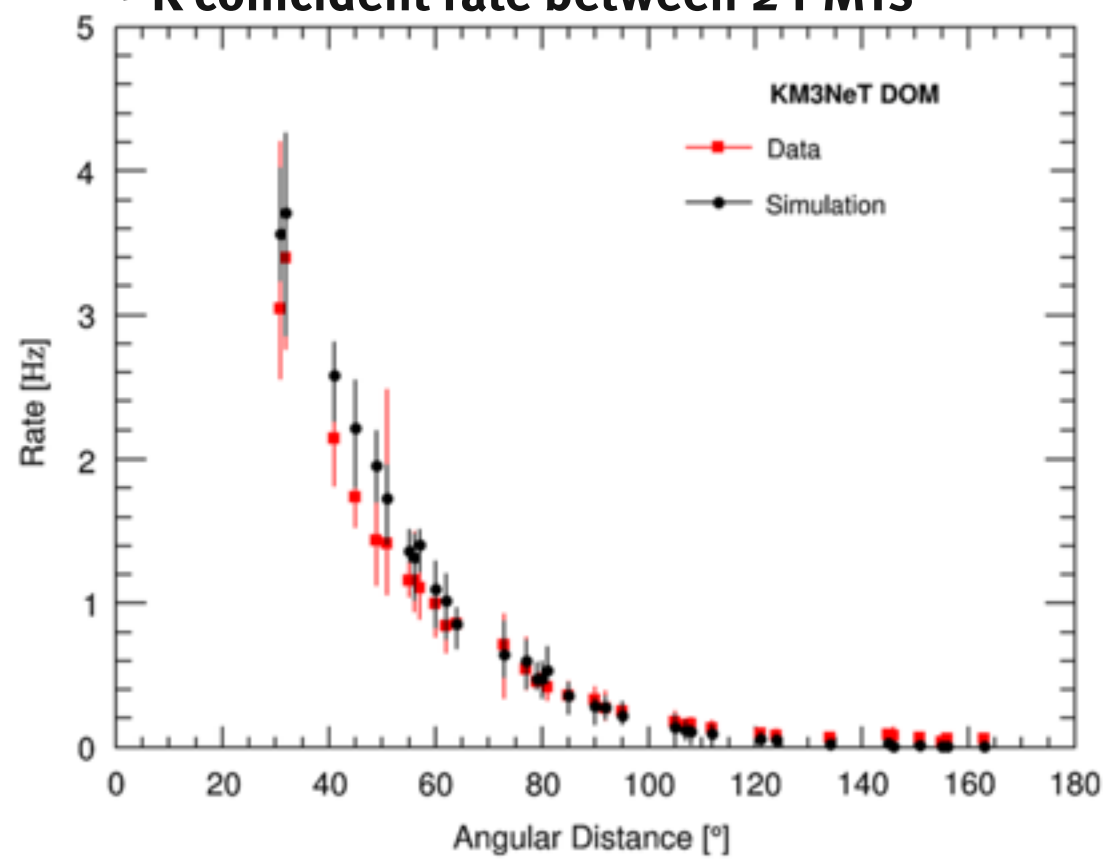
Borog et al.

single PMT rate

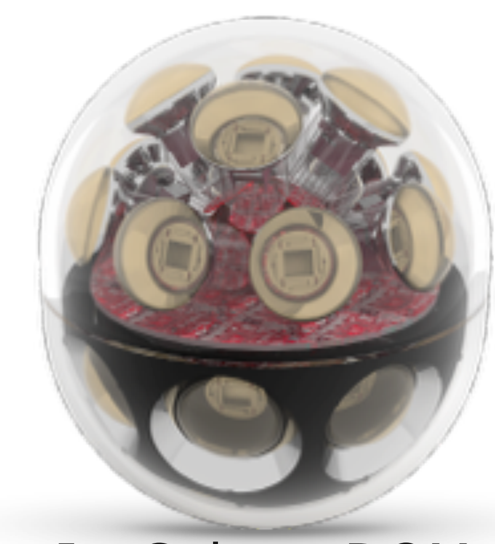


KM3NeT, Eur. Phys. J. C (2014)

^{40}K coincident rate between 2 PMTs



- Successful in-situ application in KM3NeT
- Under development for IceCube-Gen2 (mDOM)
  (alternative to baseline design with single, large PMT)



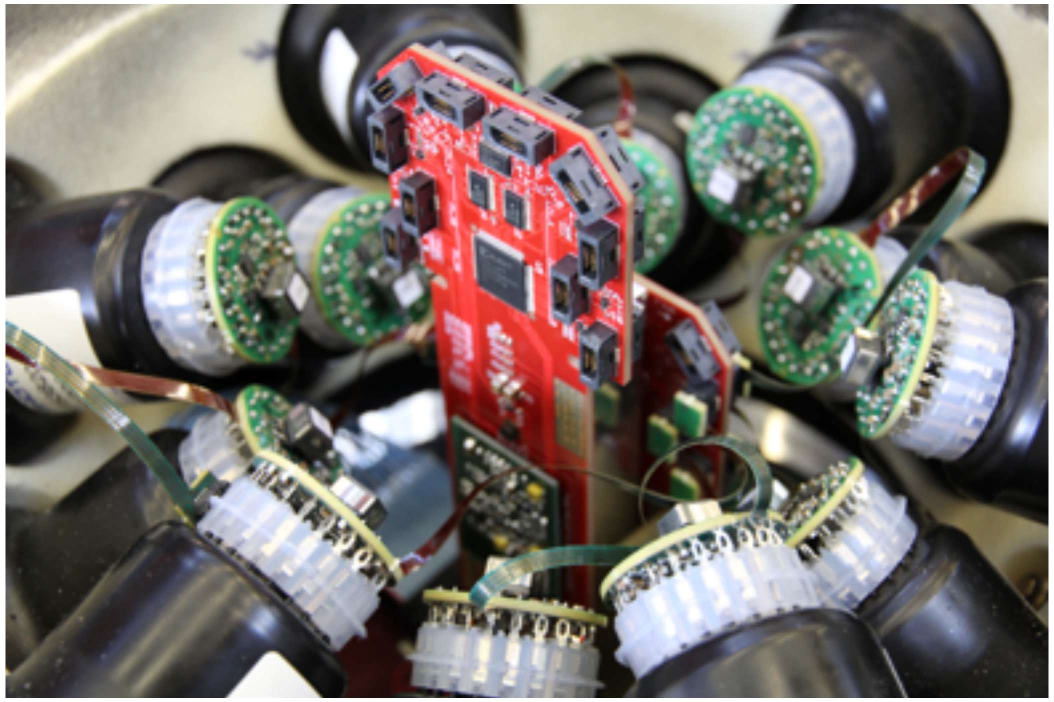
IceCube mDOM

living.knowledge
WWU Münster

Challenges for multi-PMT modules

- Tight available space and power constraints
- Large number of readout channels
- Production of large number of small (3”) PMTs (up to several 100k)
- Availability of PMTs with suitable properties

KM3NeT DOM



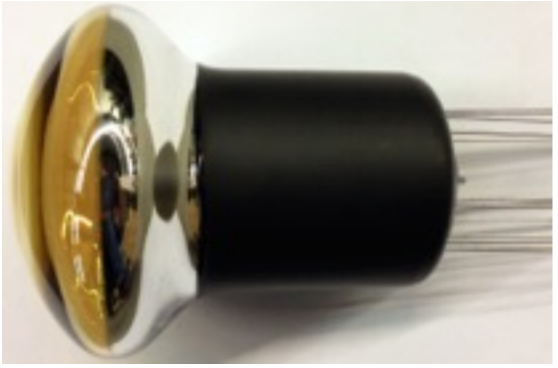
Photomultipliers

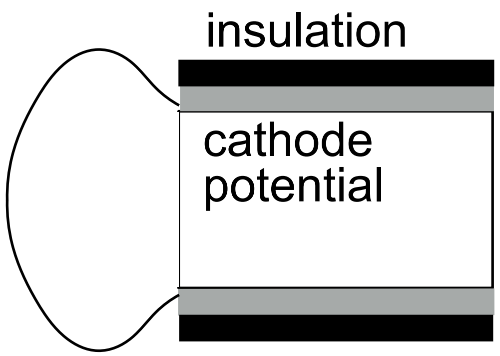
- Available PMTs with adequate properties (based on KM3NeT criteria)

Hamamatsu R12199-02

- – photocathode Ø = 80 mm
- – length = 98 mm / cylinder Ø = 52 mm
- – TTS (FWHM) = ~3.5 ns
- – peak-to-valley ratio = ~3.5
- – gain ~5×10^6 @ ~1100 V

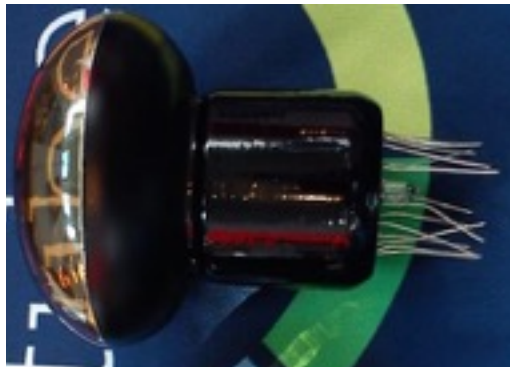
Hamamatsu R12199-02 HA





improves dark count for cathode @ −HV

ETEL 9320 KFL



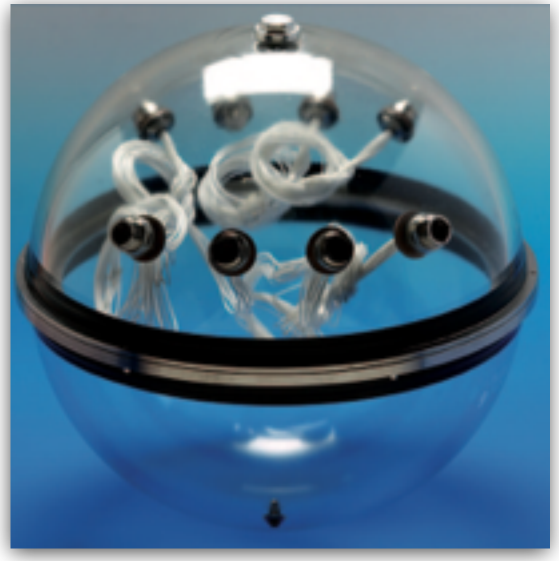
- – photocathode Ø = 87 mm
- – length = 95 mm / cylinder Ø = 52 mm
- – characteristics under investigation

- Potential other manufactures: HZC (China), MELZ (Russia)

Mechanics: Pressure vessel

- Spherical glass vessels (borosilicate glass) routinely used in deep-sea exploration
  - transparent to optical light
  - high compression strength (~1400 N/mm² (MPa))
  - typ. sizes 13", 17" with thickness 15–20 mm
  - inert to salt water
  - low price
- Challenges for usage in ice: max ∅ ≲ 14" (bore hole size) → additional space for electronics needed
  - 14" sphere with cylindrical extension (developed with Nautilus)
  - glass thickness: 14 mm
  - pressure rating: 700 bar (to be tested)
  - Production with same technique as "standard" glass spheres → comparable low price

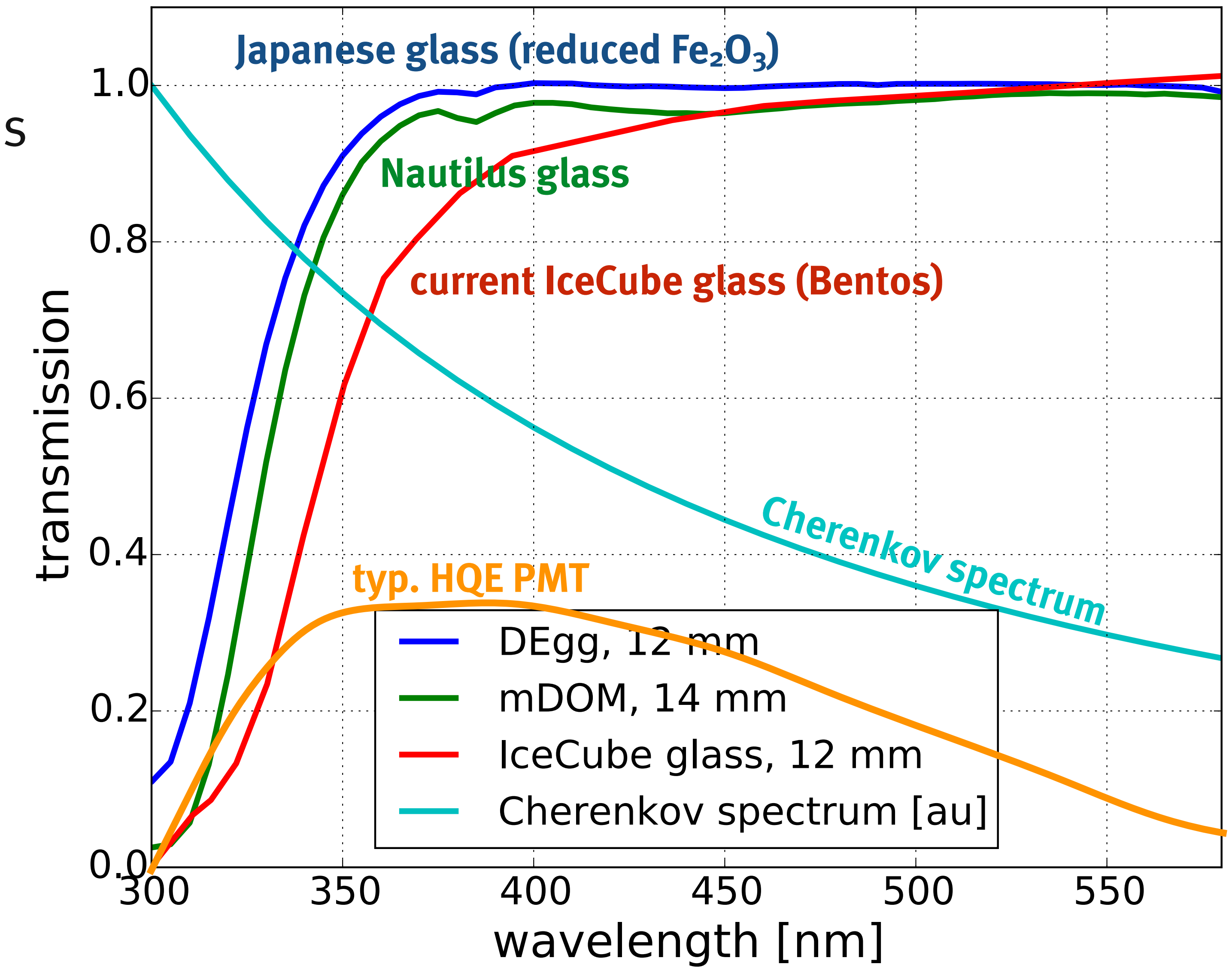
© Nautilus MARINE SERVICE GmbH



IceCube mDOM pressure vessel

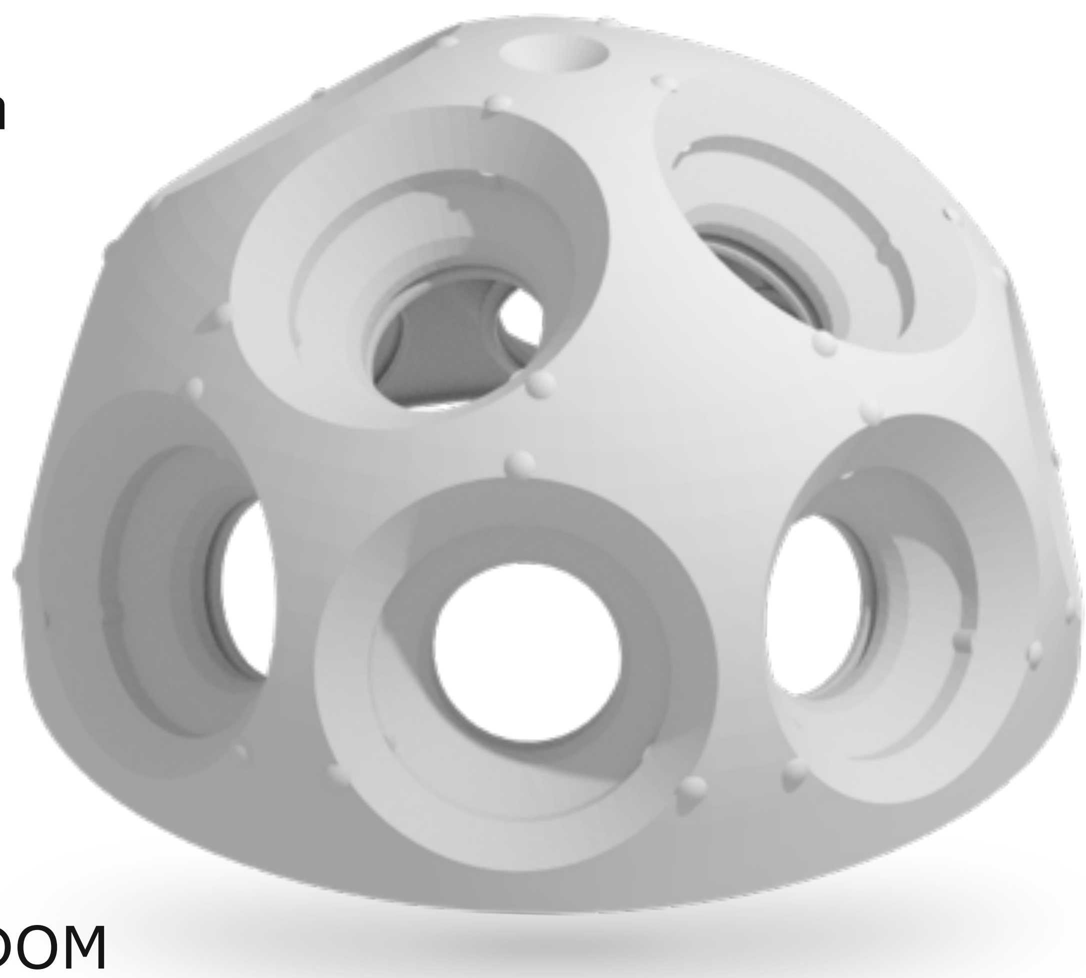
Mechanics: Transmissivity

- Cherenkov photon spectrum ~ $1/\lambda^2$
  → transparency in UV range important
- Significant differences between glasses of same material (borosilicate glass)
- But also radioactive contamination important → optical background



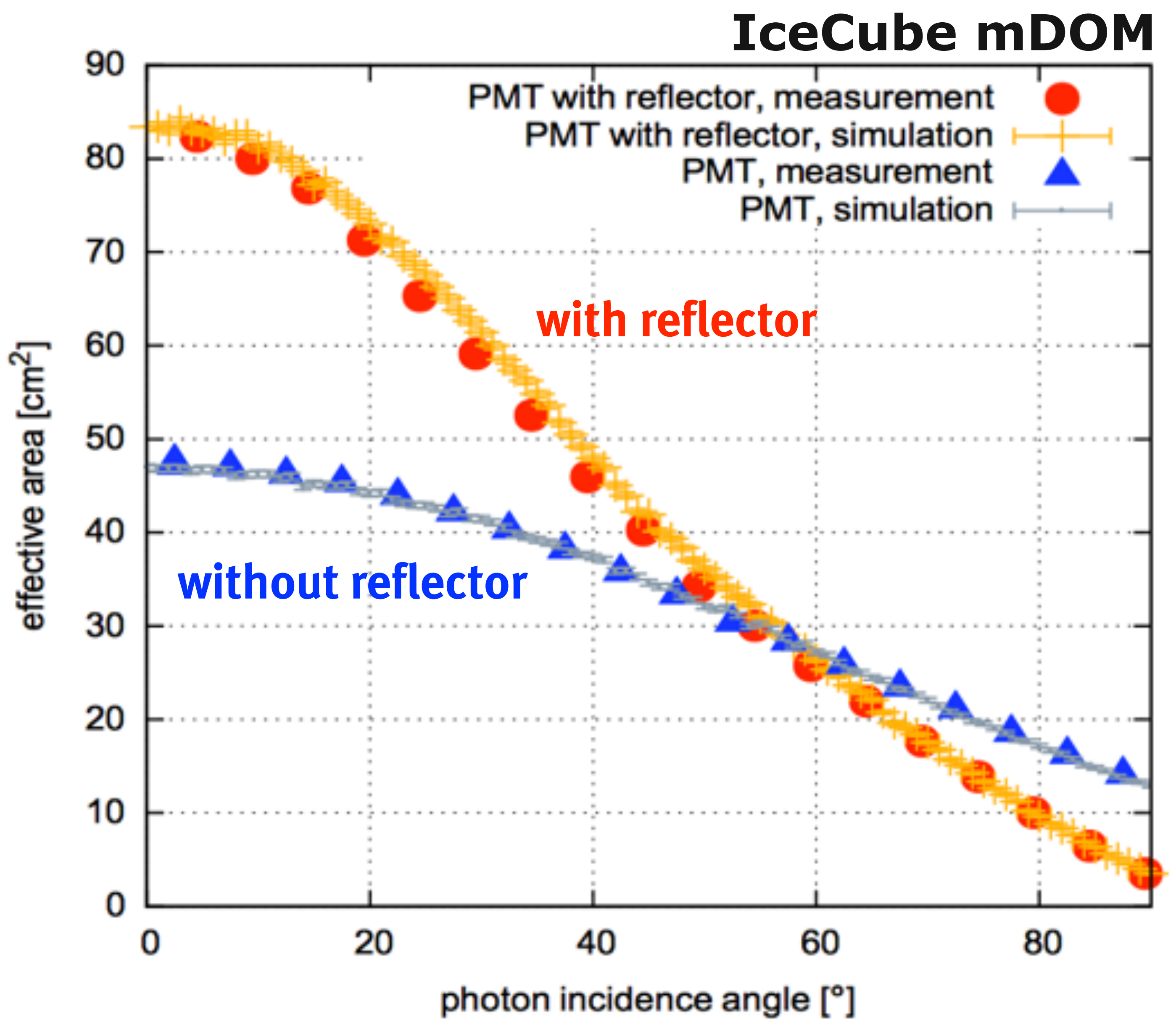
Mechanics: PMT holding structure

- Complex structure with e.g.
  - O-ring cavity (sealing and PMT fixation)
  - distance holders for “gel-coating” of PMT
- Nowadays, fast and well-priced production via laser sintering (type of 3D-printing)
- Allows for mounting of reflective cones



IceCube mDOM

Effect of reflectors on angular acceptance

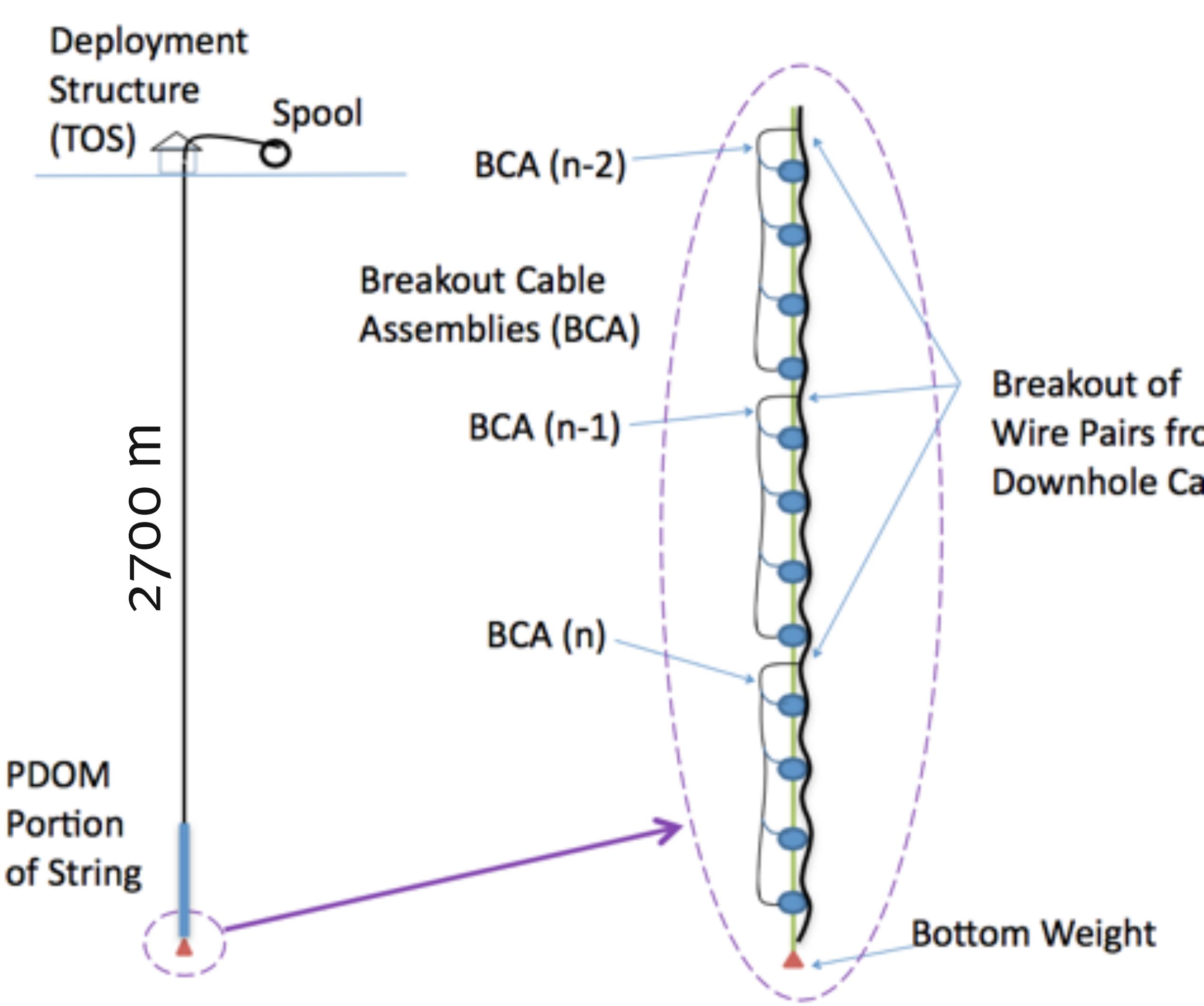


- Reflectors significantly increase directionality of PMT

Electronics: General considerations

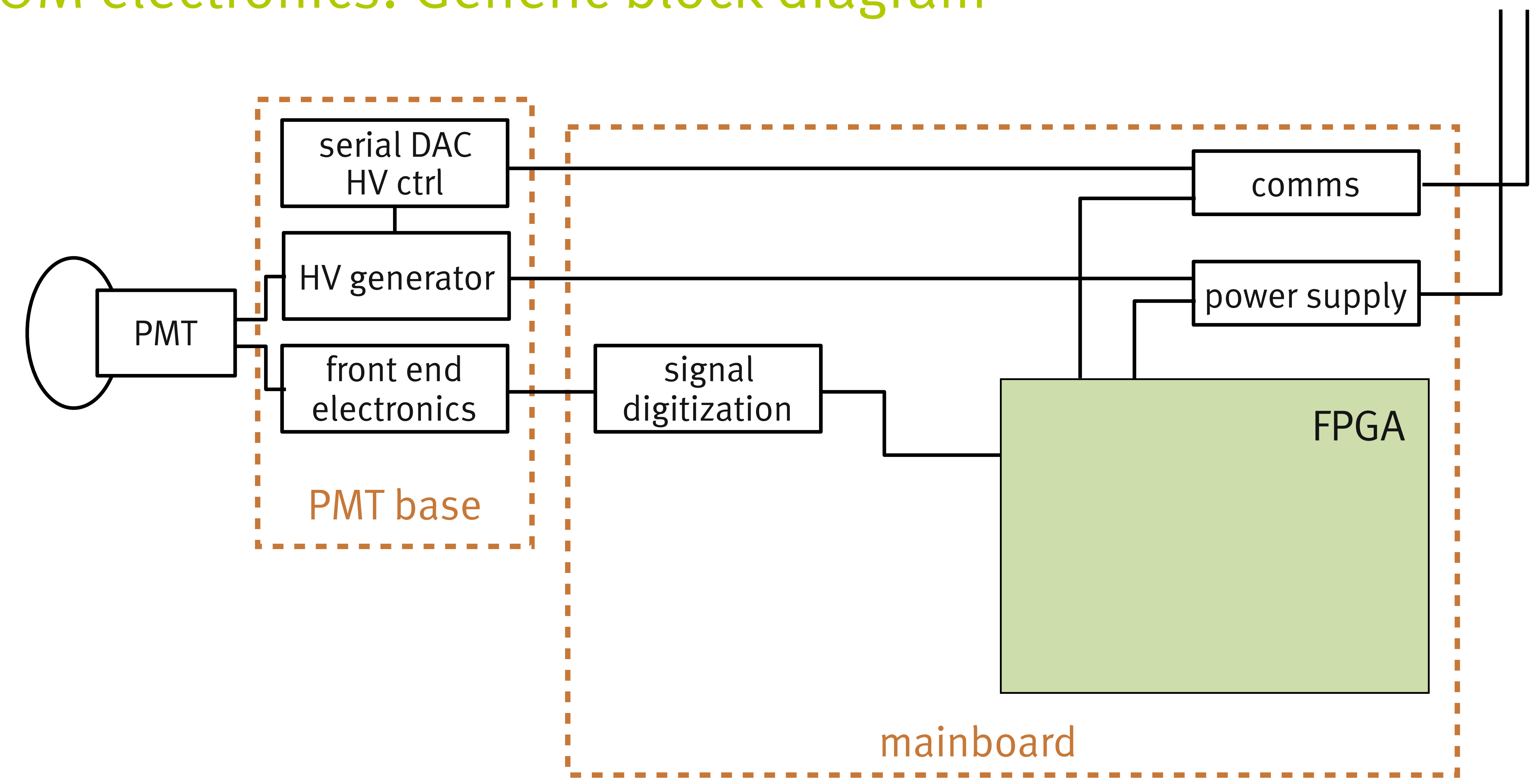
- Detectors at remote locations (deep sea, South Pole)
  → power consumption crucial factor
- Particulate important for IceCube
  - power (+ comm.) through ~20 copper wire pairs
  - power usage limited by voltage drop from surface
    → max. ~3.4 W per DOM (3 DOMs per wire pair)
    → ~60 mW per PMT (readout/digitization + HV)
    (mainboard, power supply etc. subtracted)

IceCube cabling scheme



IceCube Coll. *PINGU LOI* arXiv:1401.2046 (2014)

DOM electronics: Generic block diagram



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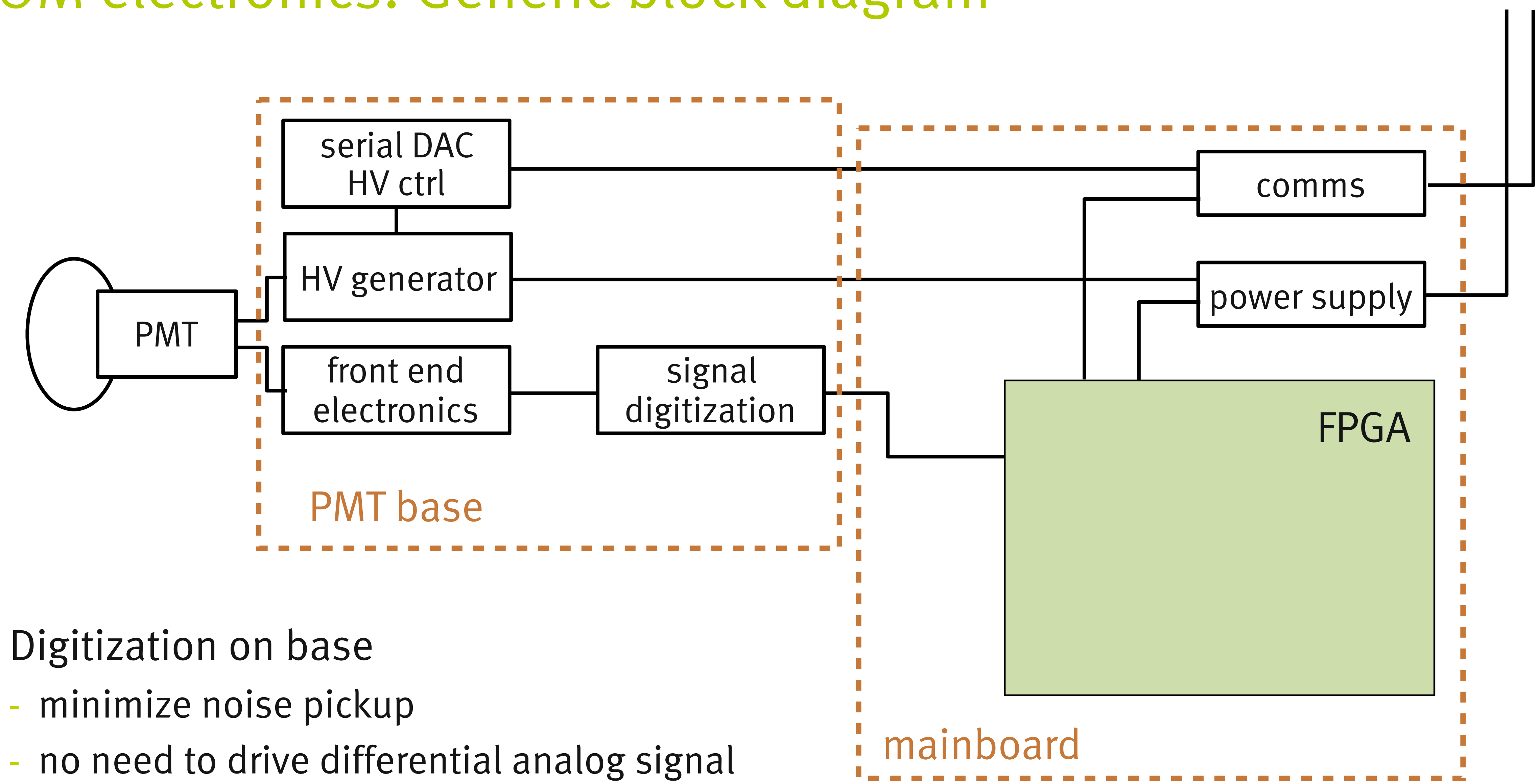
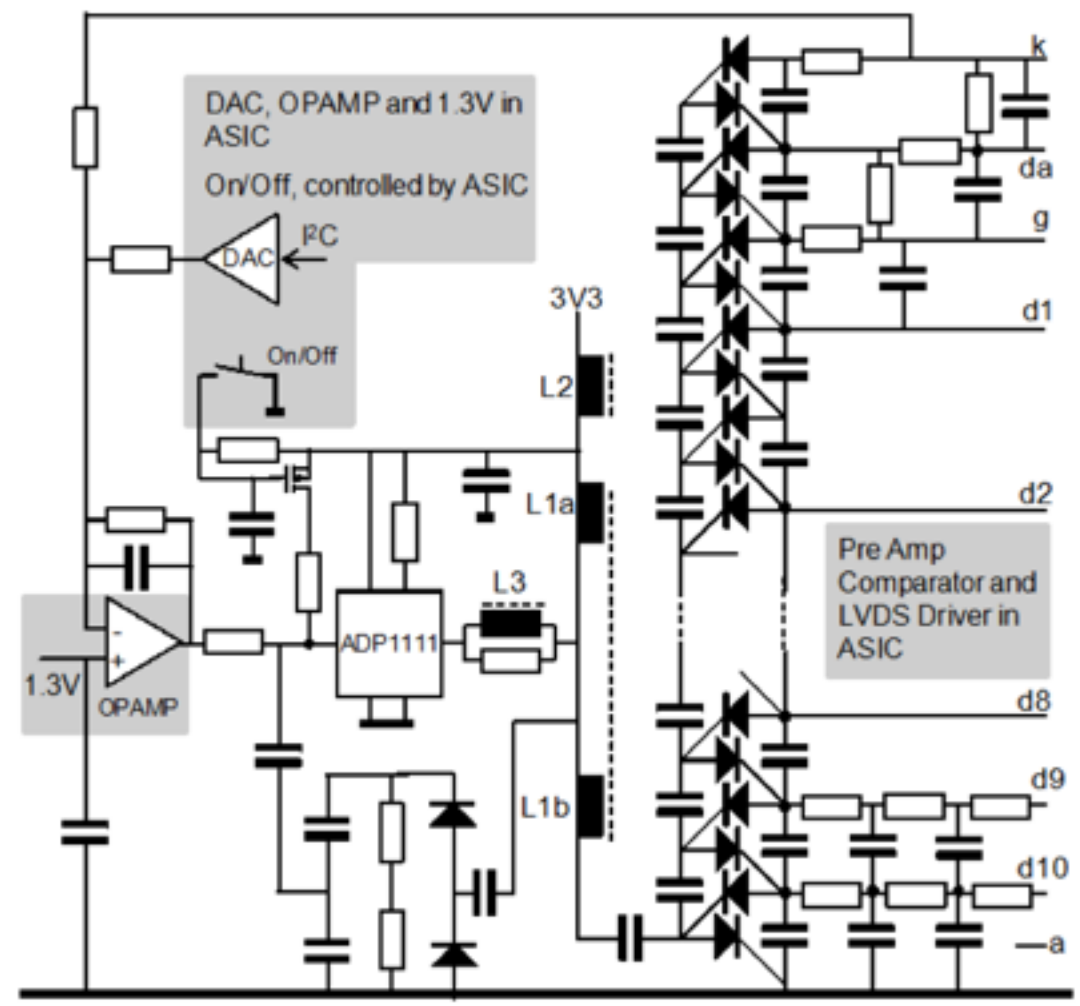


- Digitization on base
  - minimize noise pickup
  - no need to drive differential analog signal
  - requires low footprint components

Electronics: PMT base

Timmer, 2010 JINST 5 C12049

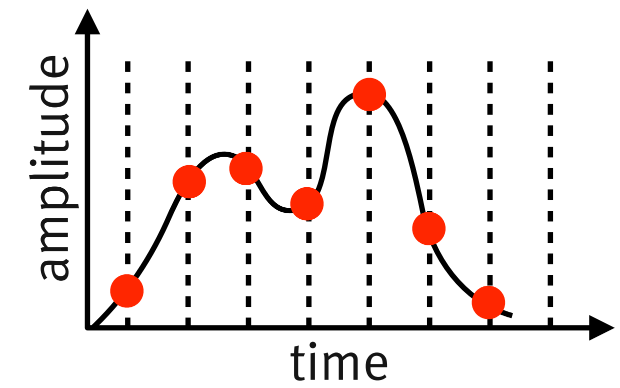
- Requirements
  - individually adjustable HV (~1000 V)
  - low-power
  - compact design
- KM3NeT design (Nikhef) (also used for IceCube-mDOM)
  - Cockroft-Walton circuit
  - power consumption 3–4 mW
  - fits on single side of PMT base



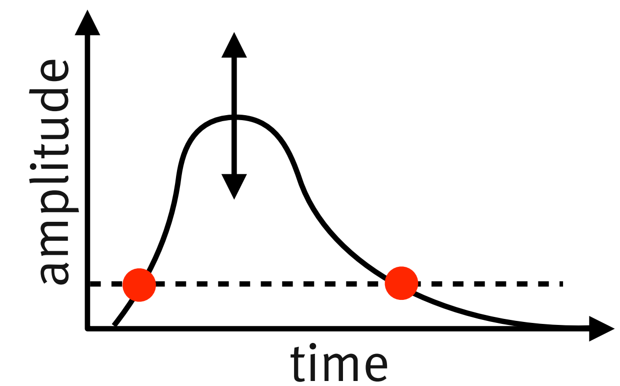
Electronics: Readout schemes

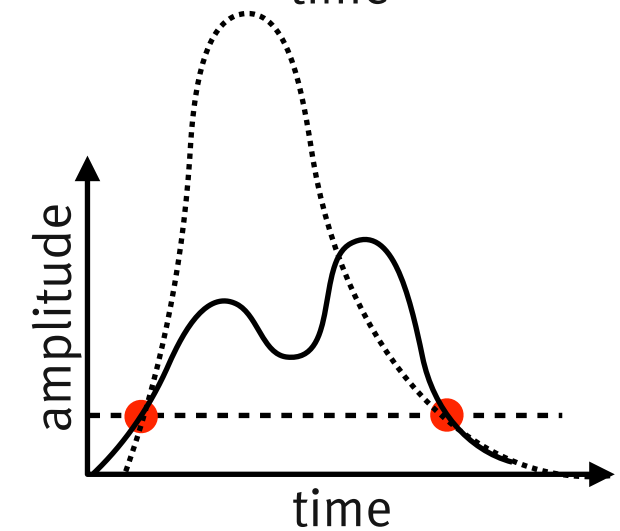
- Standard signal digitization: sampling of amplitude in fixed interval (IceCube baseline DOM: flash ADC with 14 bit, 250 MHz)

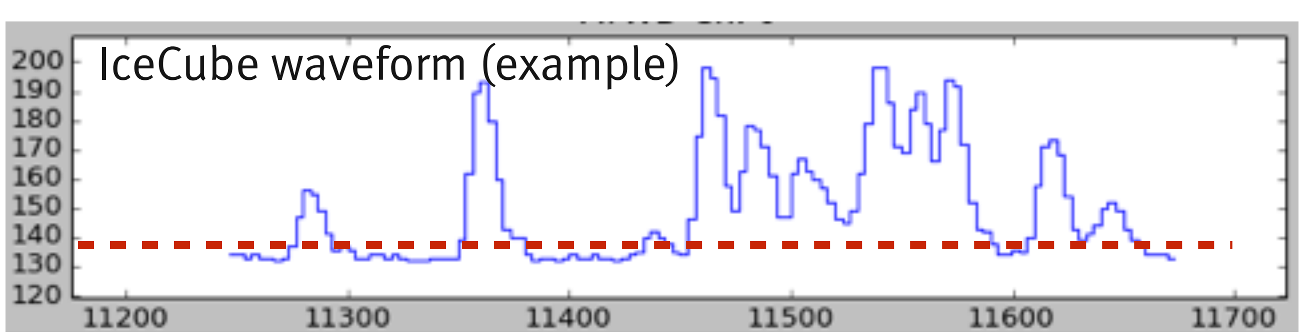
  → disadvantage: high power consumption, size



- Alternative: Time-over-Threshold (ToT)
  - shape of single photon pulse known (amplitude variable)
    → sample with comparator (time-over-threshold, KM3NeT)
  - advantages: low-power, small footprint (fits on backside of base)
  - disadvantage: ambiguities for fast consecutive signals (particularly the case for IceCube because of large scattering in ice)



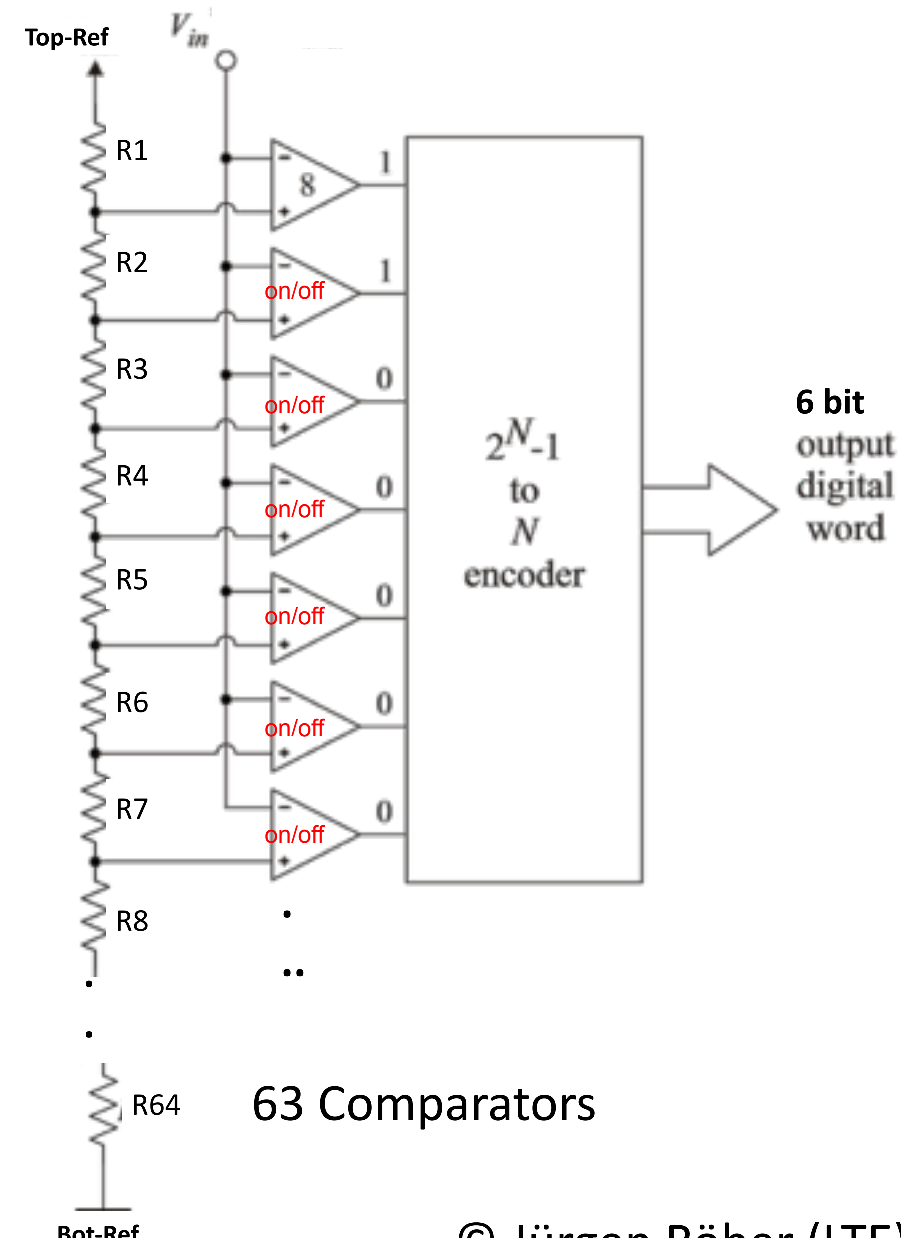




Electronics: Multi-comparator readout

- Multi-comparator design for IceCube mDOM
- Challenges: limited space (backside of base) and power (~50 mW)
- Two-fold strategy
  - Discrete design: allows for ~4 comparators (under development @ DESY-Zeuthen)
  - ASIC design: 63 comparators with 6 bit encoder (under development @ LTE Univ. Erlangen)
- Output: pseudo-digital signal (single-ended) → time-stamping in FPGA with 250–500 MHz

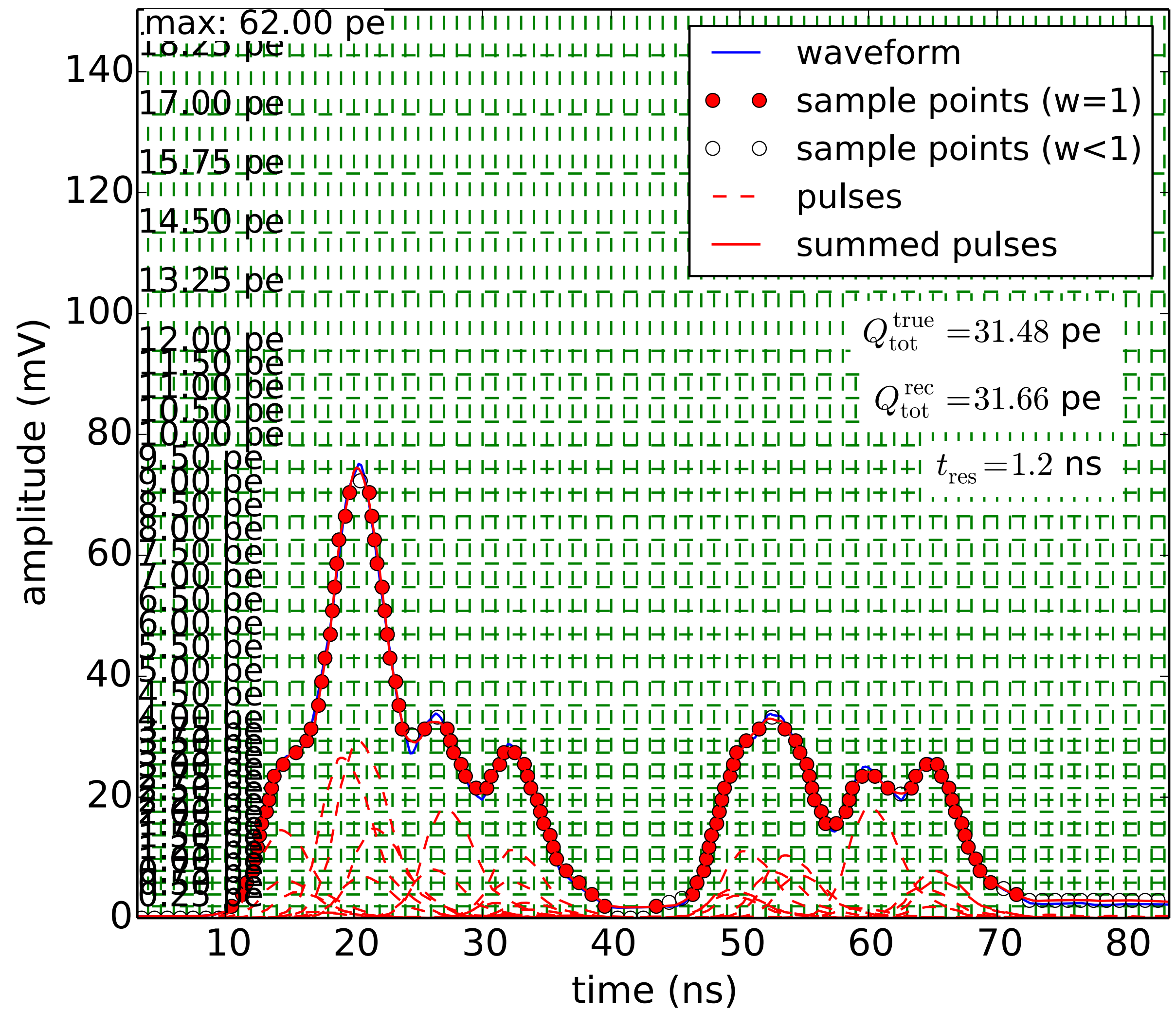
mDOM 63-comparator ASIC design



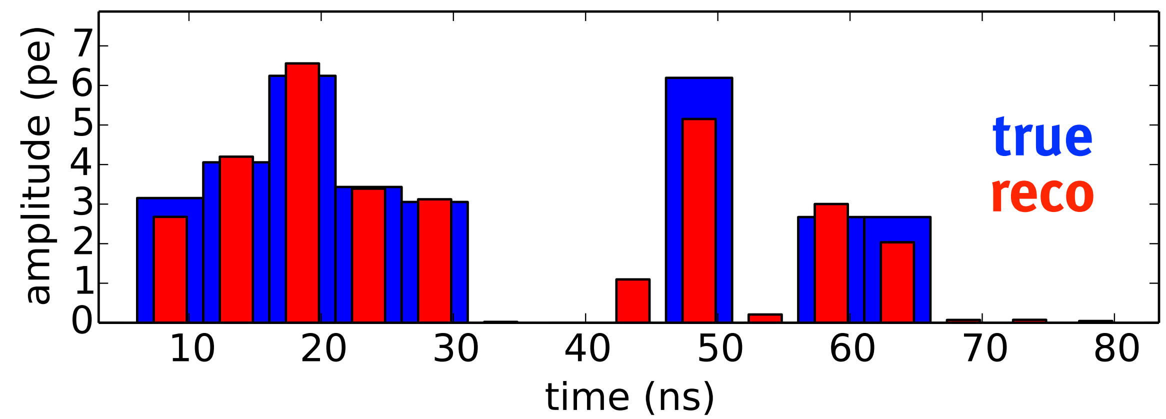
© Jürgen Röber (LTE)

Pulse reconstruction with 63 discriminators

- Encouraging first results
  - Input: 10 pulses, mean amplitude 3 pe
  - ΔCharge ‹ 1%
  - Δt(first pulse) ≲ 1 ns



- True pulse times vs. reconstructed



Summary

- PMTs still first (only) choice for low-background, single-photon detection scenarios
- Multi-PMT optical modules provide several attractive advantages compared to "standard" single-large-PMT modules
  (directionality, increased photocathode area, improved photon counting, local coincidences)
- Challenges: tight space and power constraints + costs
  - mechanics for large number of PMTs
  - readout of large number of channels, digitization of complex signals
- In KM3NeT, 31 PMTs with individual, single time-over-threshold readout
  → successfully tested in situ (deep sea)
- IceCube-Gen2 aims at advanced version for application in the deep ice
  - ASIC development for 63-comparator readout of 24 PMTs
  - optimized UV sensitivity (pressure vessel, optical gel) and mechanics
  - with moderate modification also applicable in other experiments (Hyper-K, CHIPS . . .)

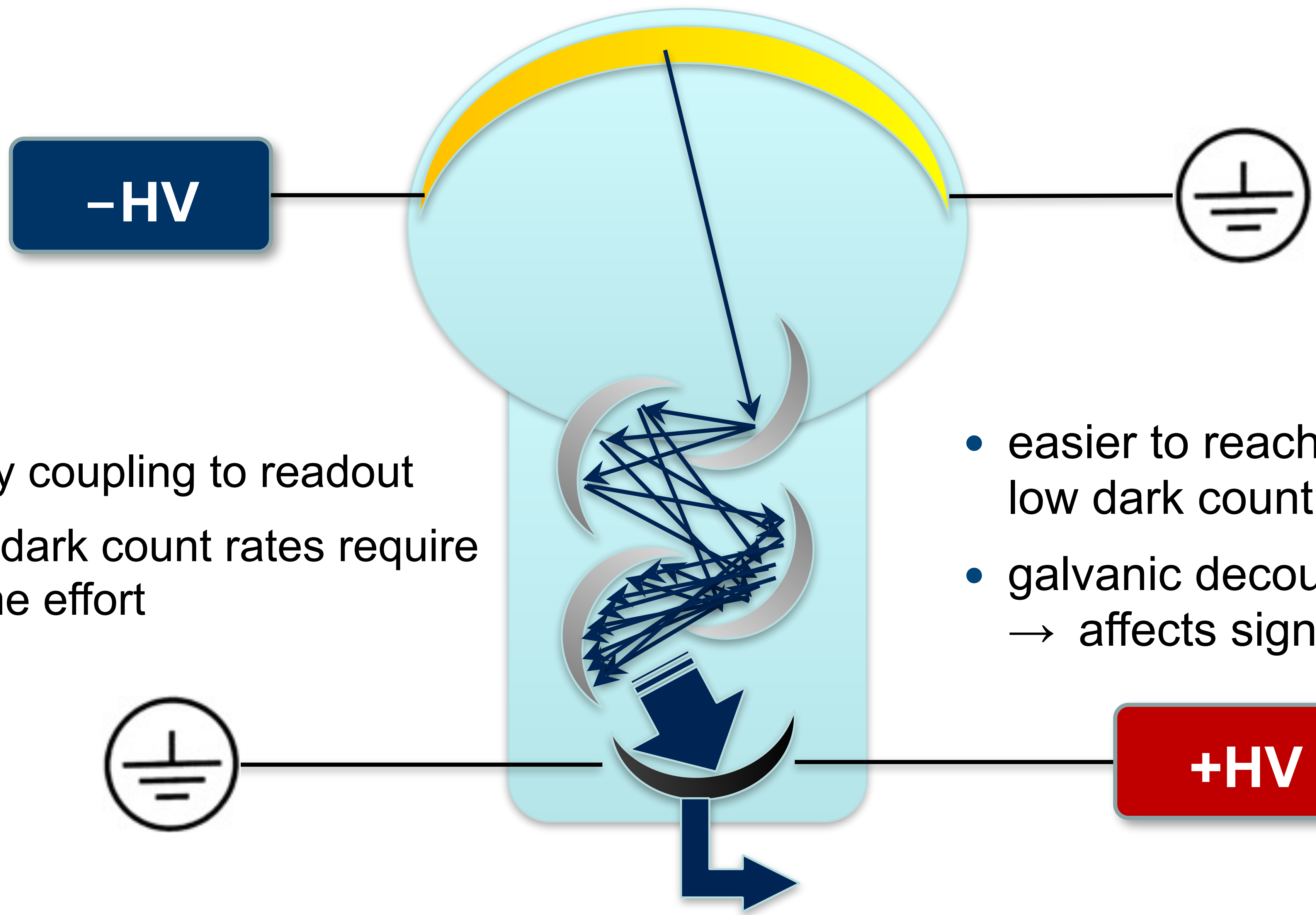
Bundesministerium
für Bildung
und Forschung

Backup

Photomultipliers

Requirements (KM3NeT)	
quantum efficiency @ 470 nm	> 20%
transit time spread (σ, FWHM)	< 2 ns, < 4.6 ns
gain	$> 2 \cdot 10^6$
supply voltage	< 1400 V
dark count rate @ 15°C	< 1.5 kHz
peak to valley ratio	> 3
length	< 120 mm
power consumption incl. base	< 4 mW

PMTs: HV polarity and background



- easy coupling to readout
- low dark count rates require some effort

- easier to reach low dark count rates
- galvanic decoupling of anode → affects signal & electronics

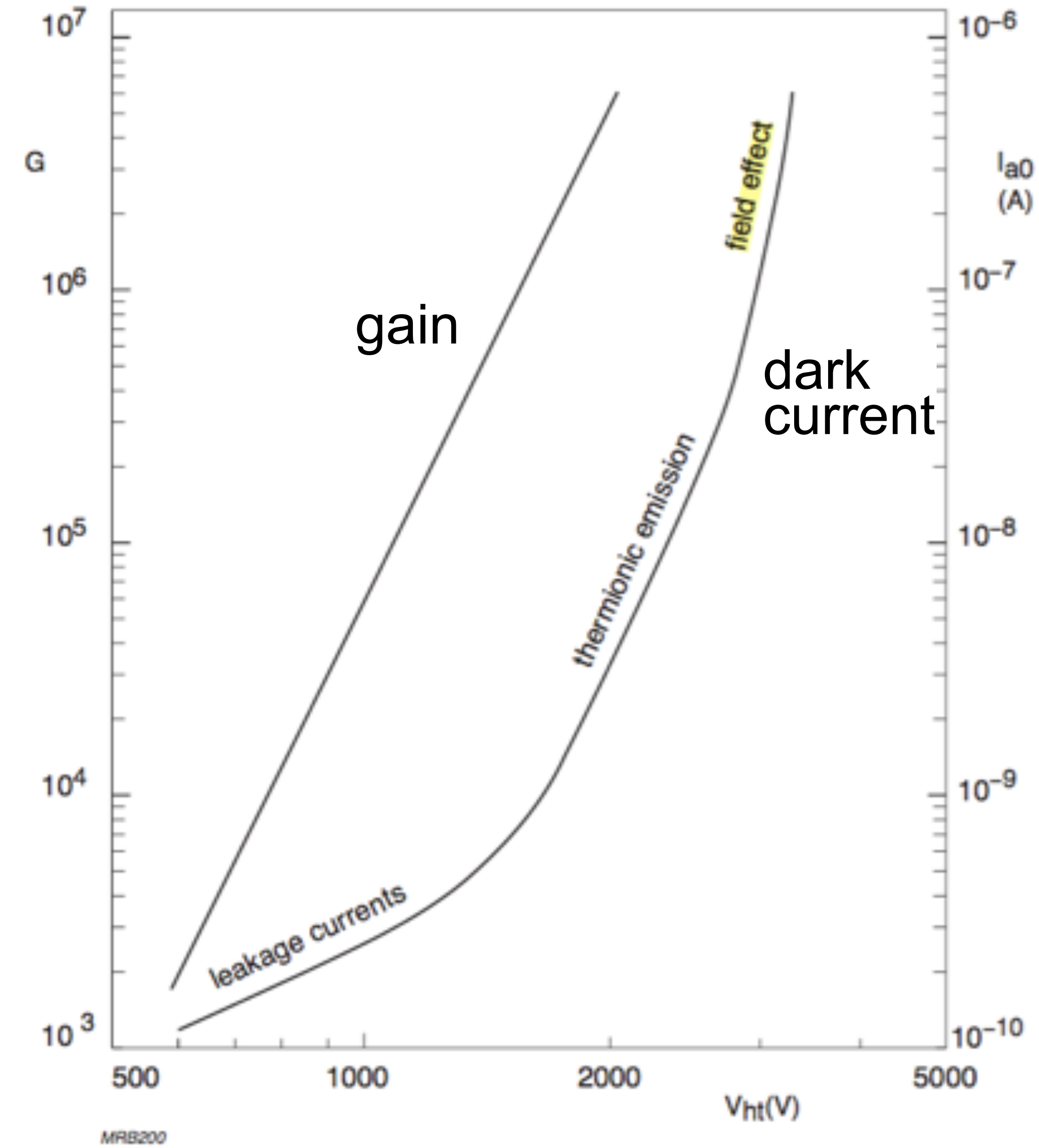
Dark-count rates

Glacial ice very radioactive clean
→ module itself dominant background source

Sources for dark count rate

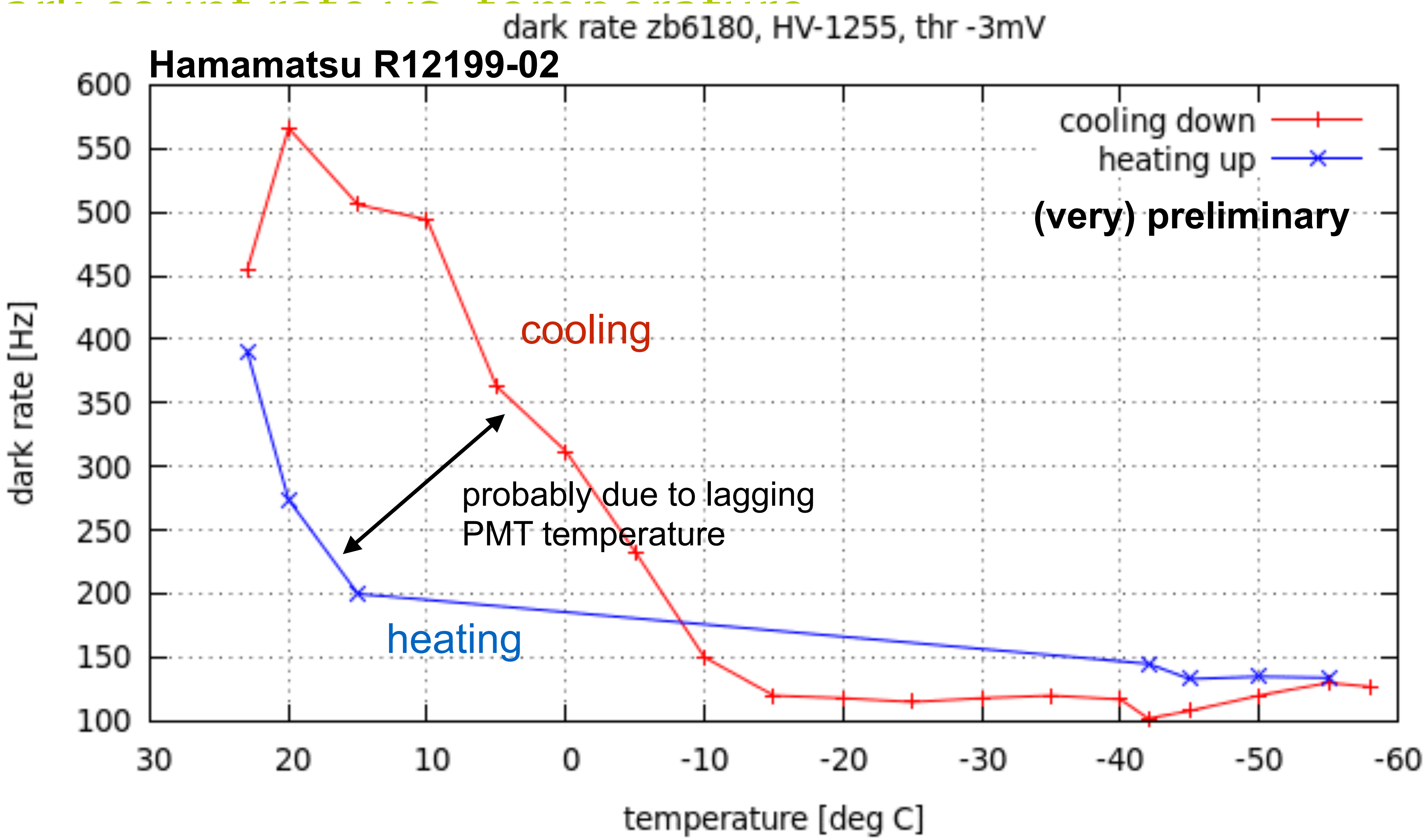
- Radioactive decays (e.g. K40)
  (glass of PMT and pressure vessel)
- Thermal emission from photocathode
  → low temperatures
- Field effect emission from PMT electrodes
  → not too high voltages/gains

Dark current



Flyckt, S.-O. & Marmonier, C. PHOTOMULTIPLIER TUBES principles & applications

Dark-count rate vs. temperature

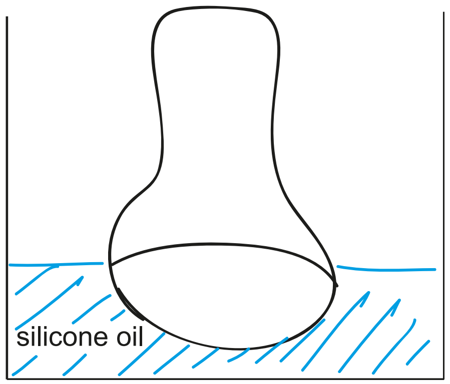


Dark-count rate reduction from ~500 Hz @ 20º C to 100−150 Hz < −30º C (thresh. ~0.3 pe, -HV)

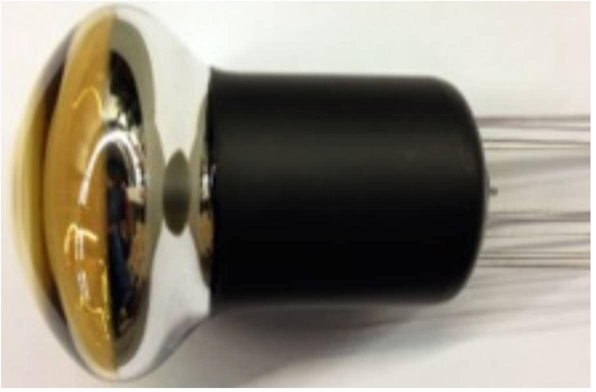
(comparison: standard IceCube 10” PMT: ~300-400 Hz @ 0.25 p.e.)

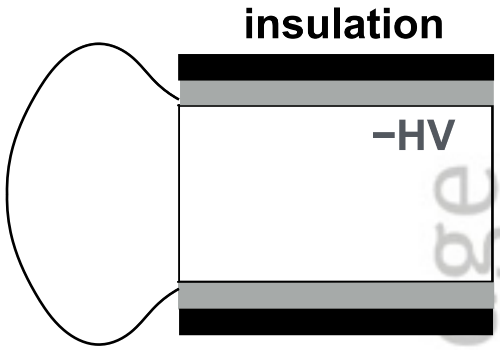
Controlling the dark-count rate with negative HV

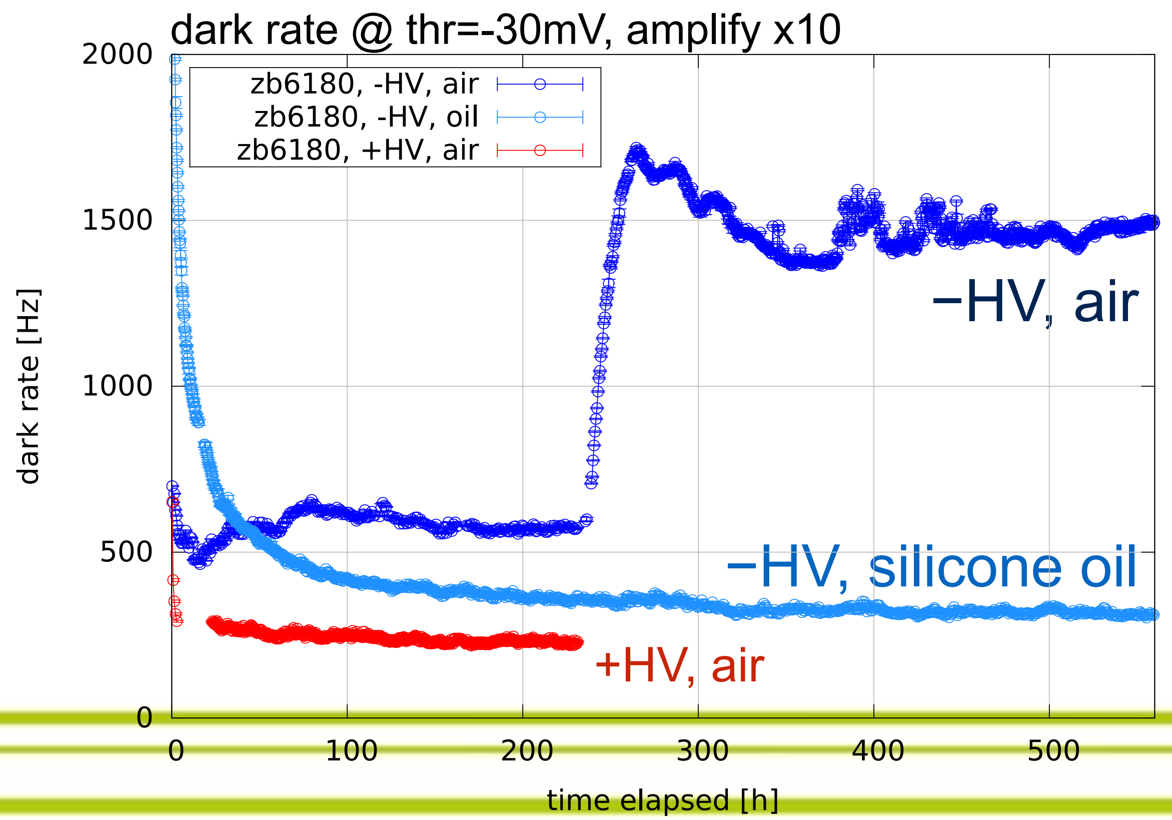
Hamamatsu R12199-02
photocathode area in silicone gel (oil)

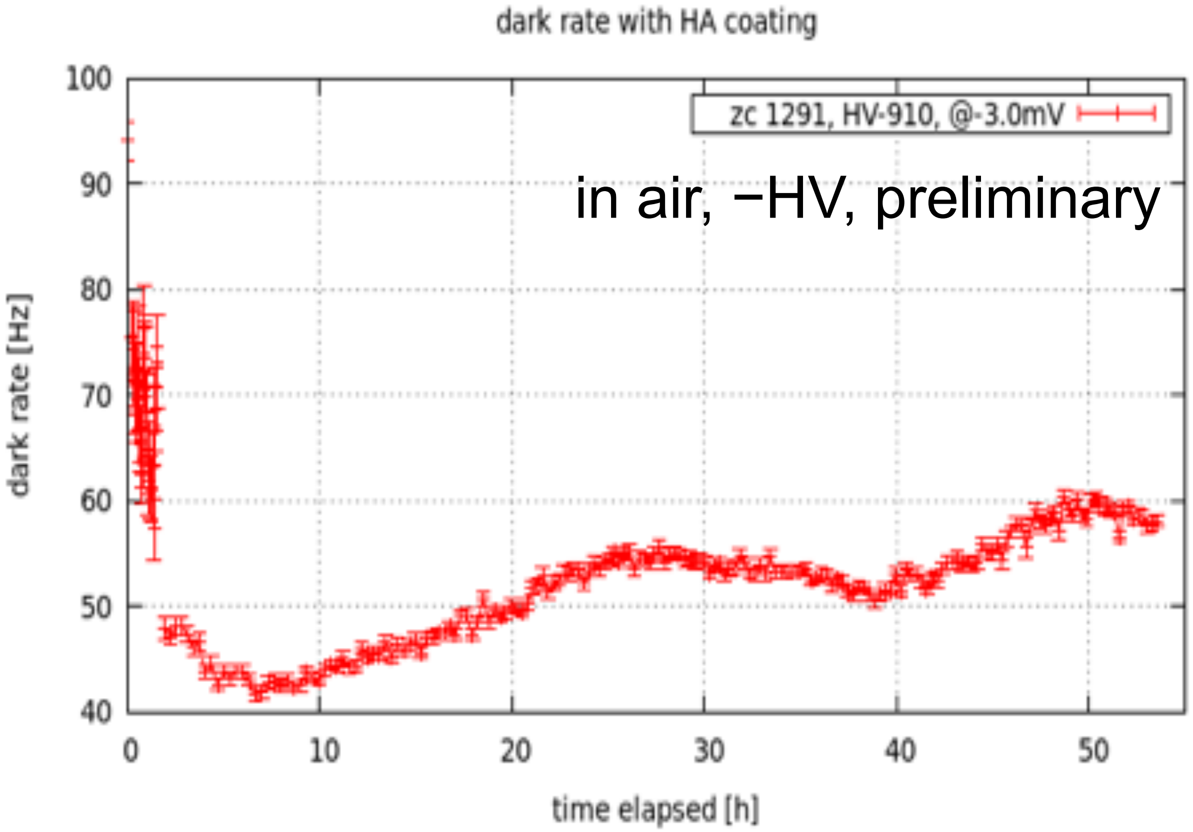


coated Hamamatsu R12199-02
(higher costs)

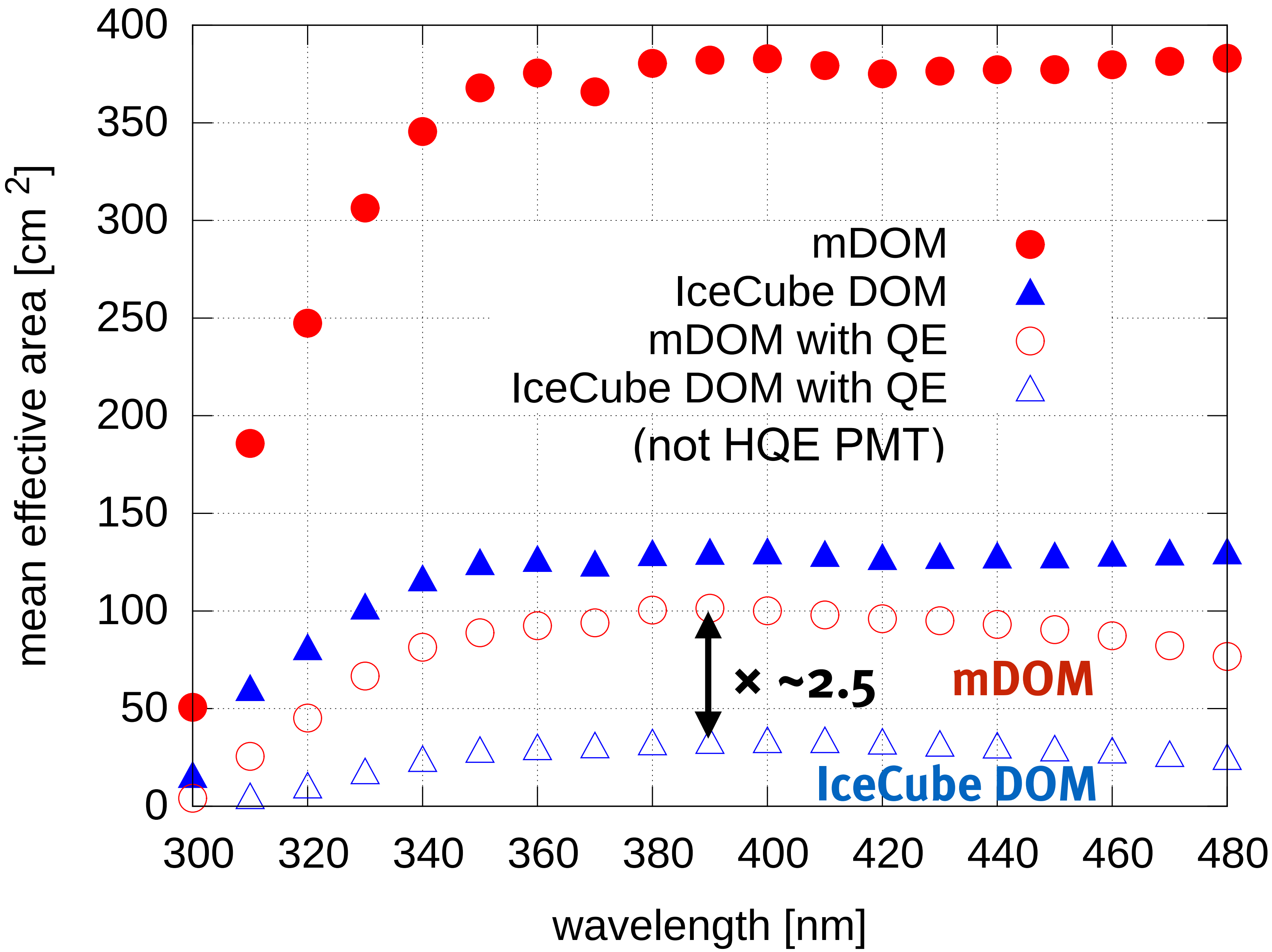








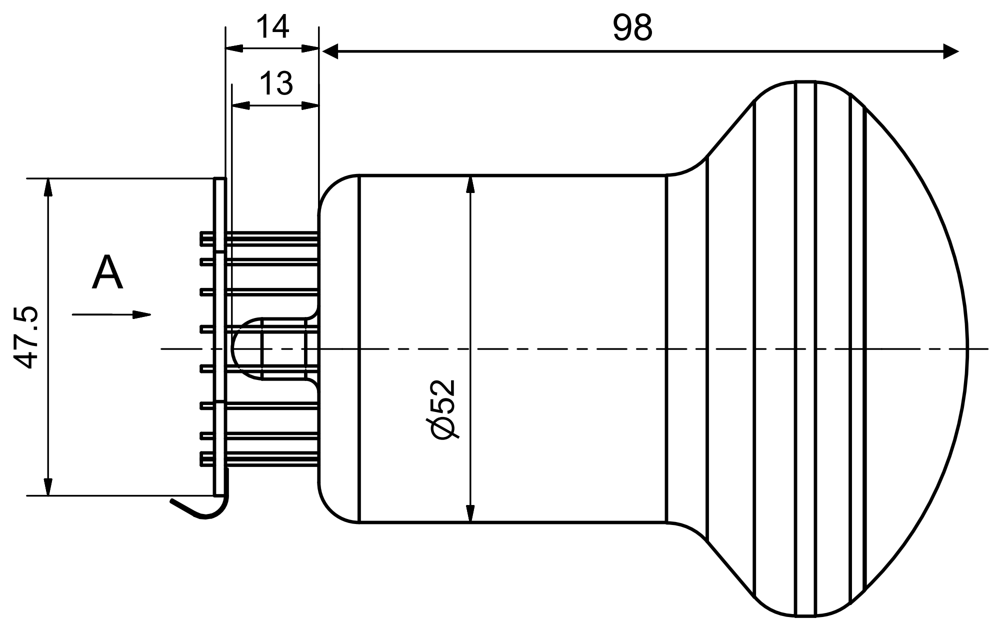
Effective area from GEANT4 simulation



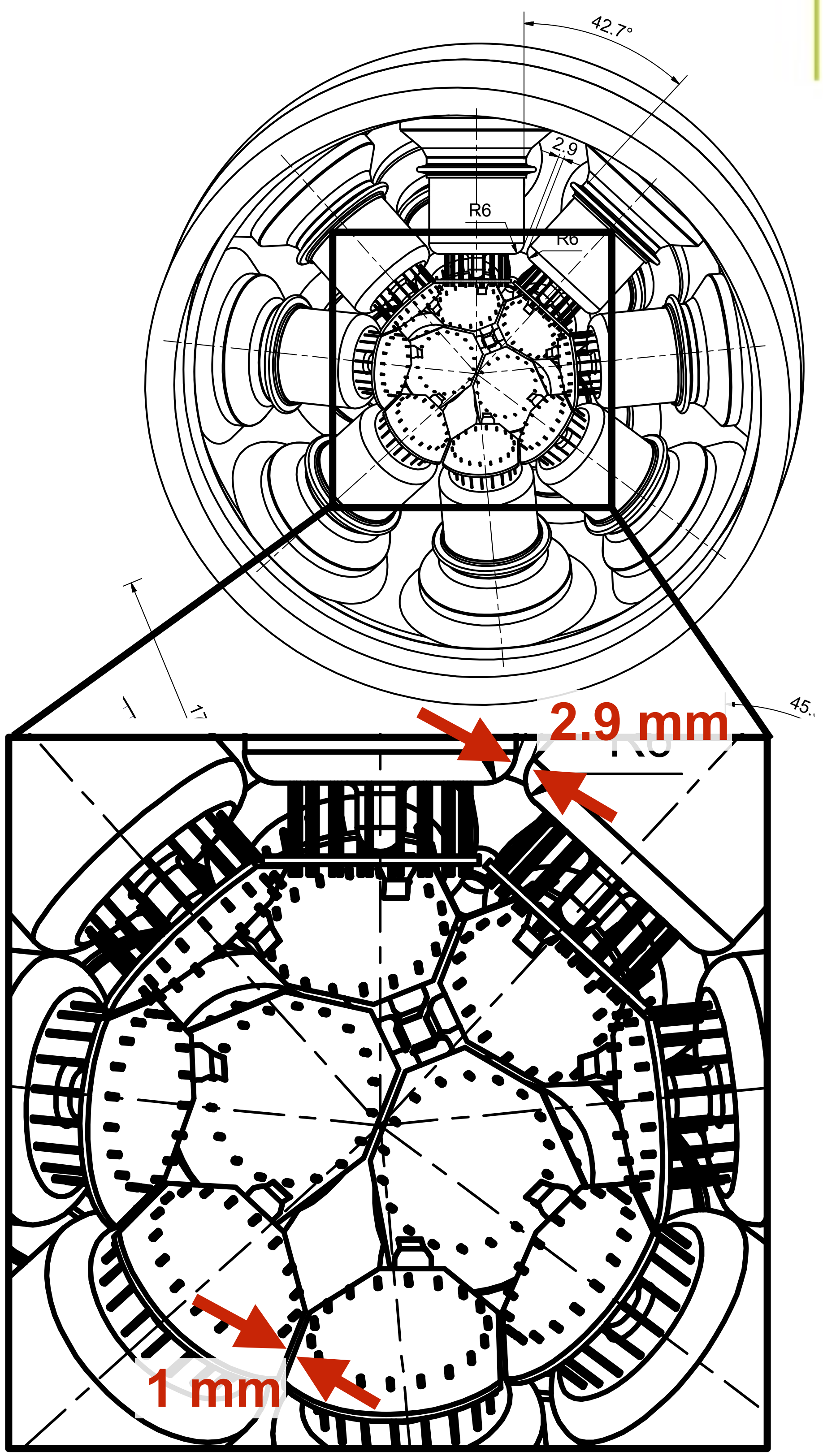
PMT form factor

- Pressure vessel diameter limited to 14" (size of borehole)
- Length (including vacuum seal) and diameter of PMT critical parameters

→ even moderately shorter PMTs highly beneficial

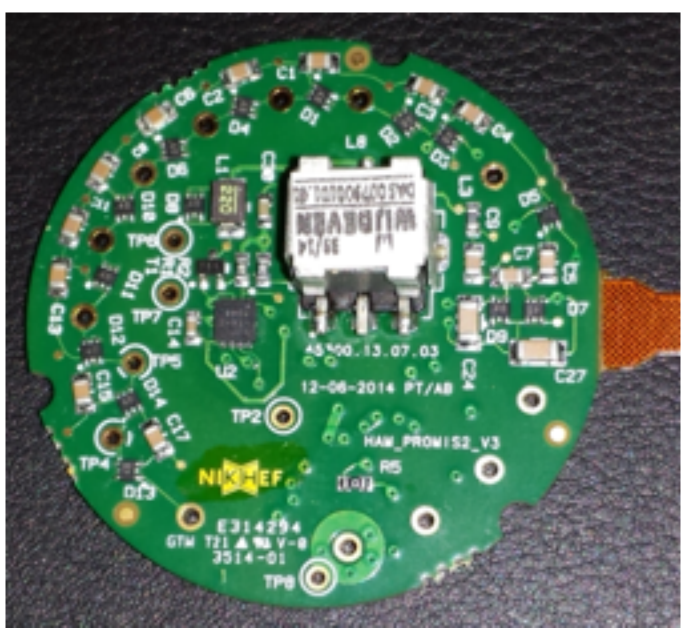


Hamamatsu R12199-02 (units in mm)

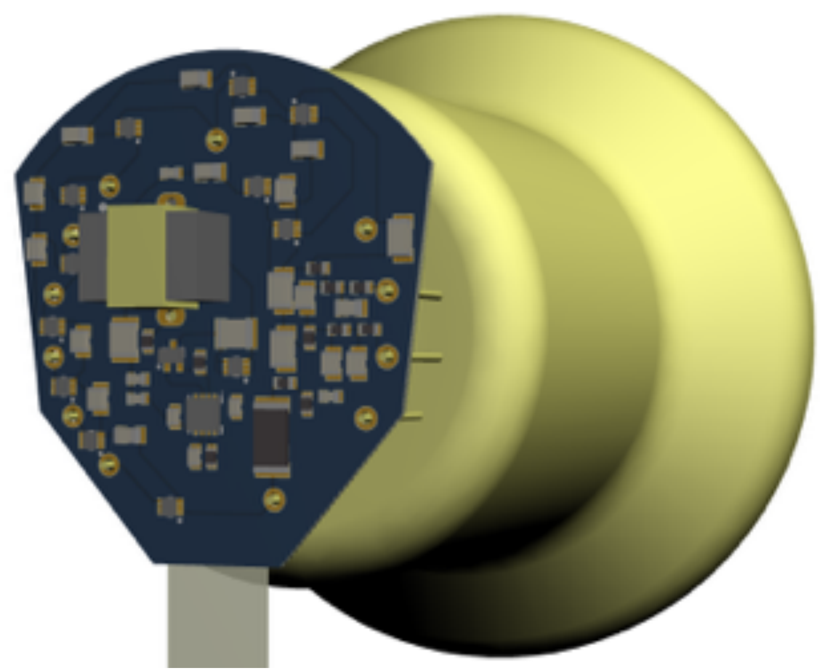


PMT base

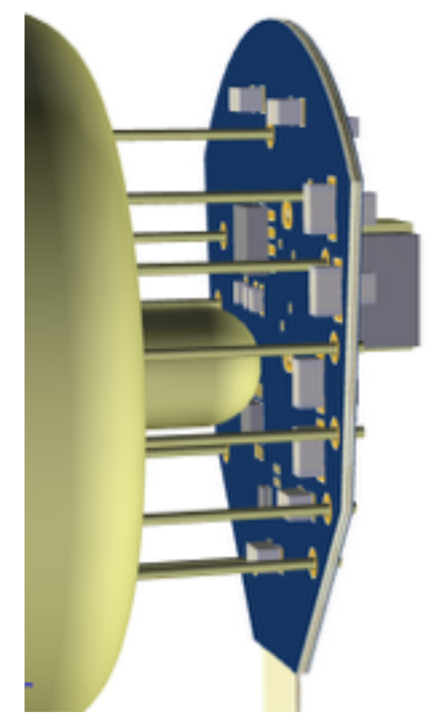
- HV generation on base; copied from KM3NeT (Cockcroft Walton design, Nikhef)
  - low power (3–5 mW)
  - small adaptions due to new board shape
- Front-end electronics for signal processing on backside



KM3NeT: HV generation



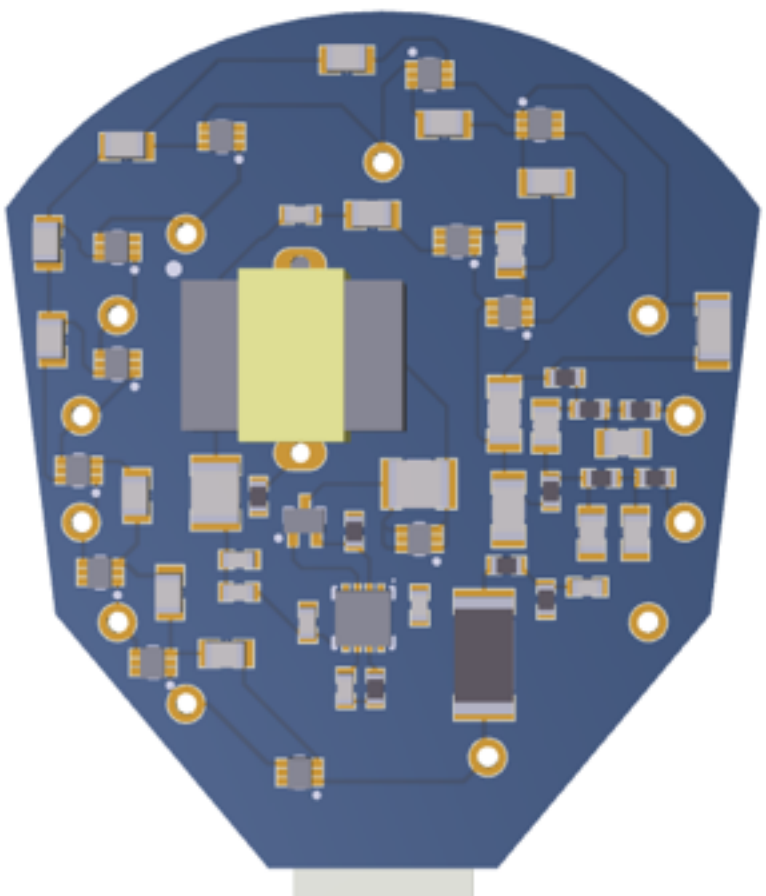
New optimized board shape with HV circuitry



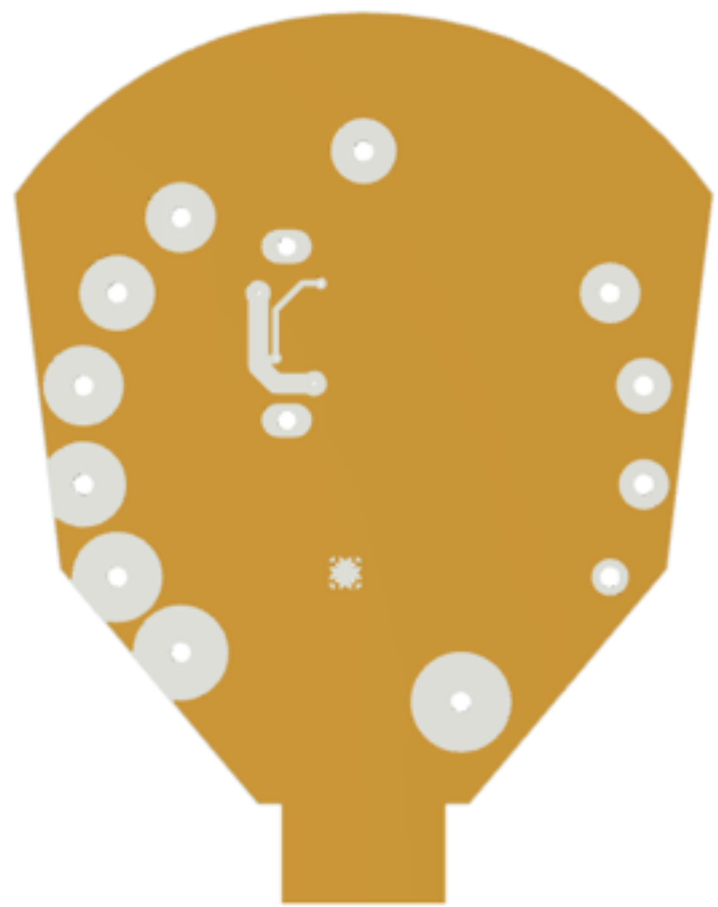
Backside with front-end electronics

Layout impressions

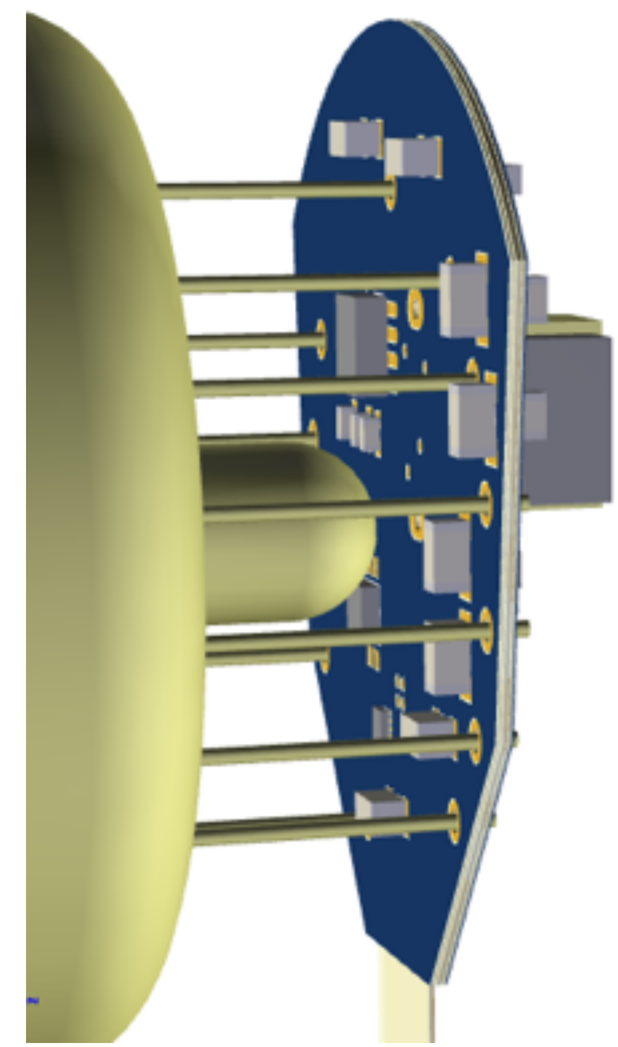
Cockcraft Walton implemented on Topside:



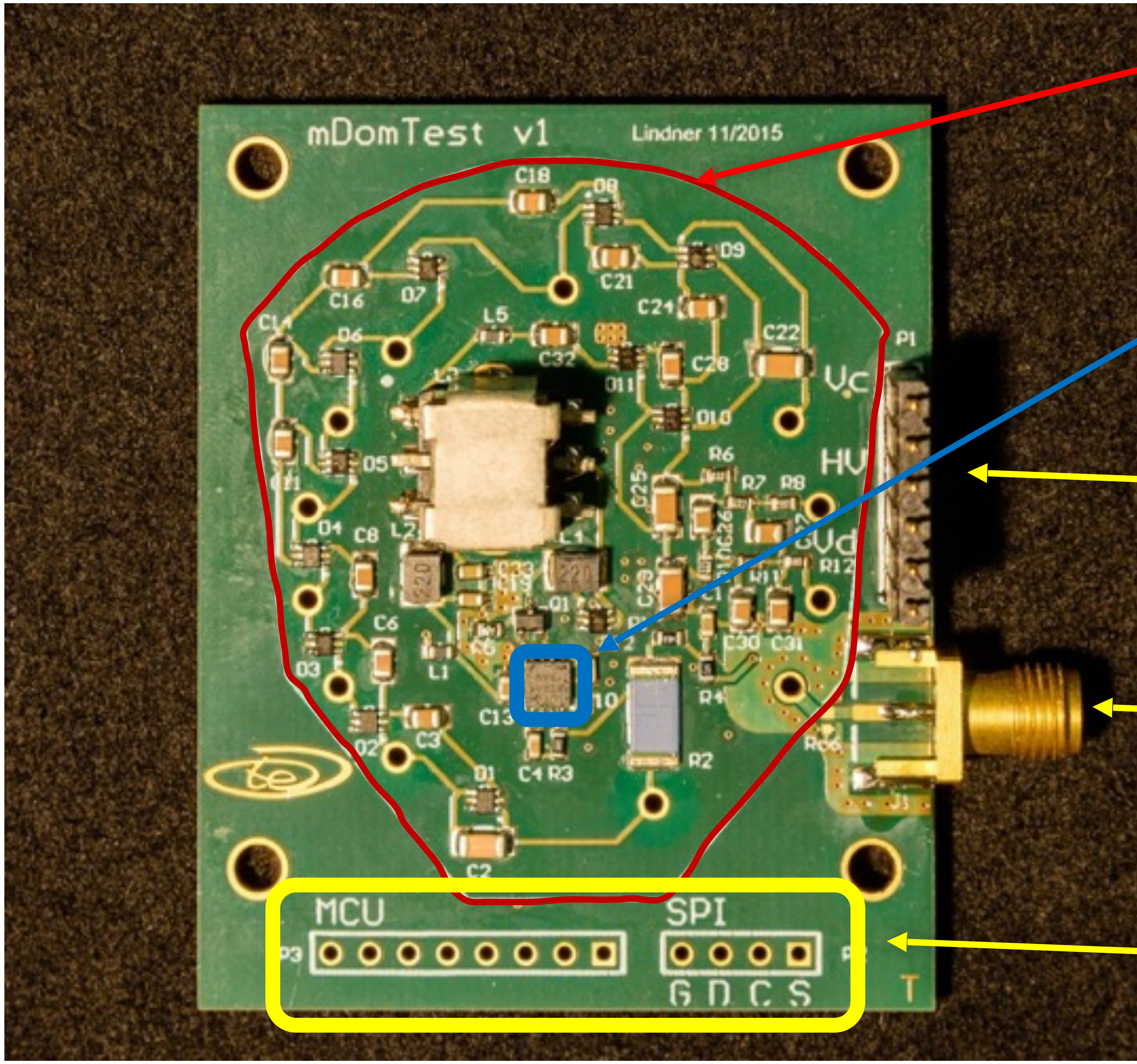
Voltage potential dependent clearance check and ground plane calculation:



Full 3d design with clearance rules for optimized room usage



Testboard Top view



Final outline

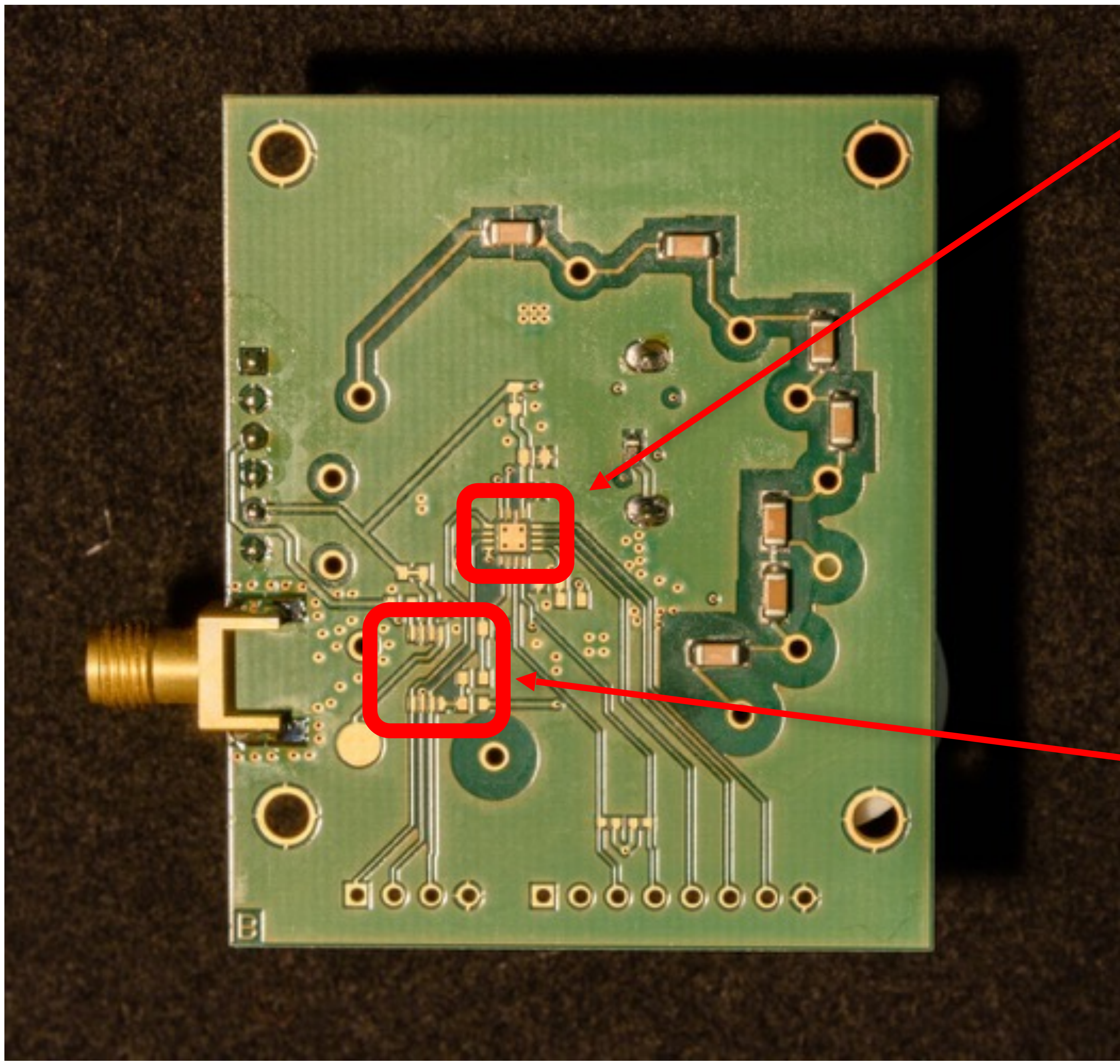
ASIC CoCo v2 (Nikhef)

Power Supply

Analog Output

Connectors for digital Communication

Testboard Top view



Microcontroller
Freescale KL03
(in Delivery)

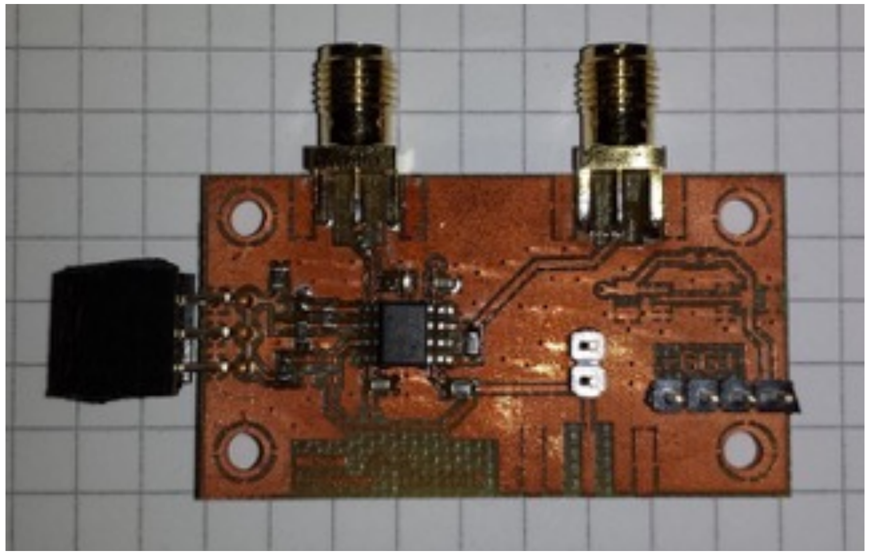
- ID
- Communication
- Monitoring
- DAC?
- Cockcraft Walton Control?

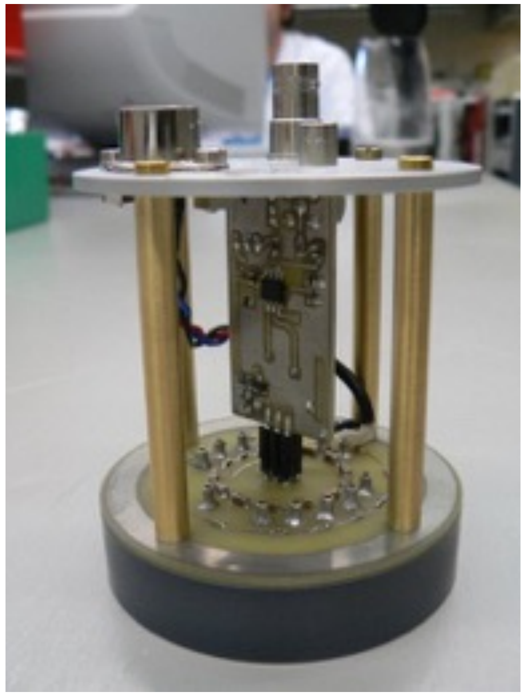
Low Power DAC
LT1662
(in Delivery)

- Ref Voltage for A/D Conversion
- HV Control Voltage

Preamplifier

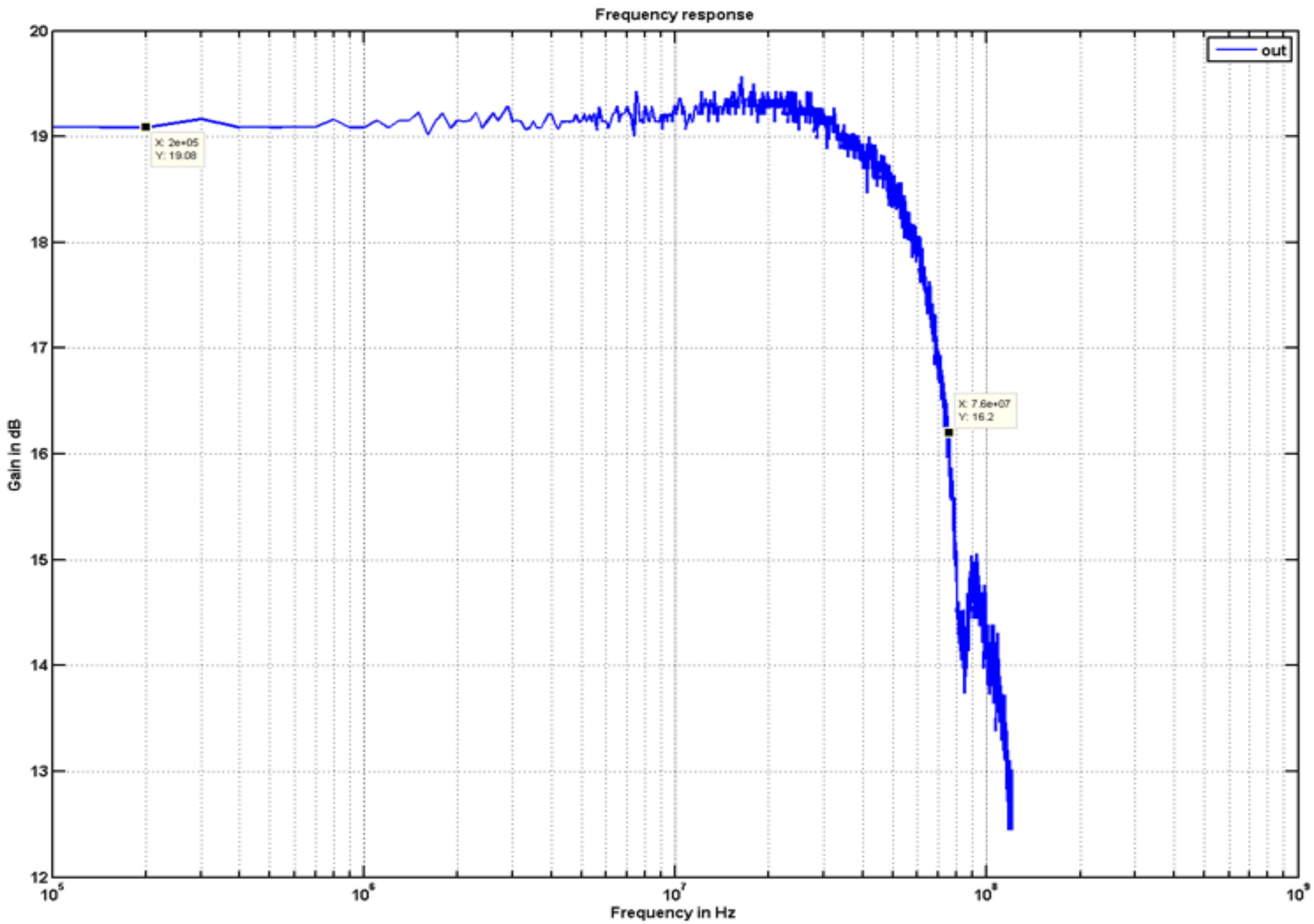
- Based on Current Feedback Opamp OPA2683
- Evaluation of
  - Inverting voltage Amplifier
  - Non-inverting voltage Amplifier
  - Charge Amplifier
- Test-PCB



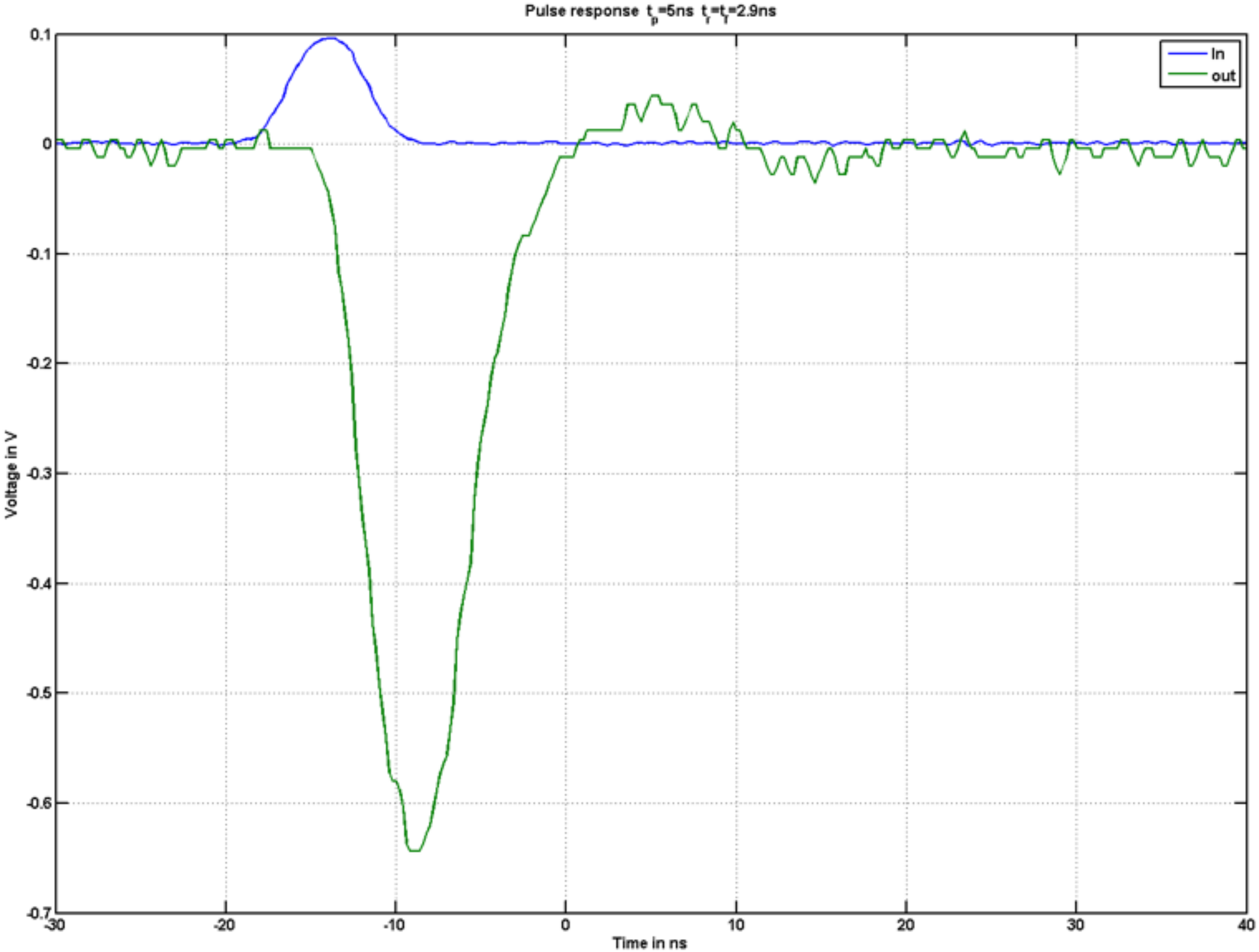


First results Preamplifier

- Power Consumption <10mW at ~75MHz Bandwidth



Preamplifier Pulse response

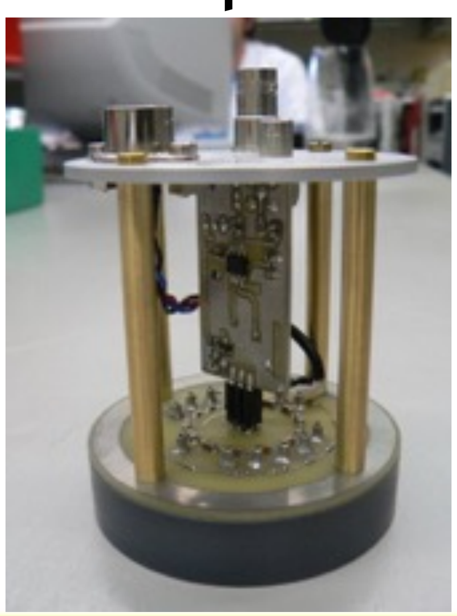


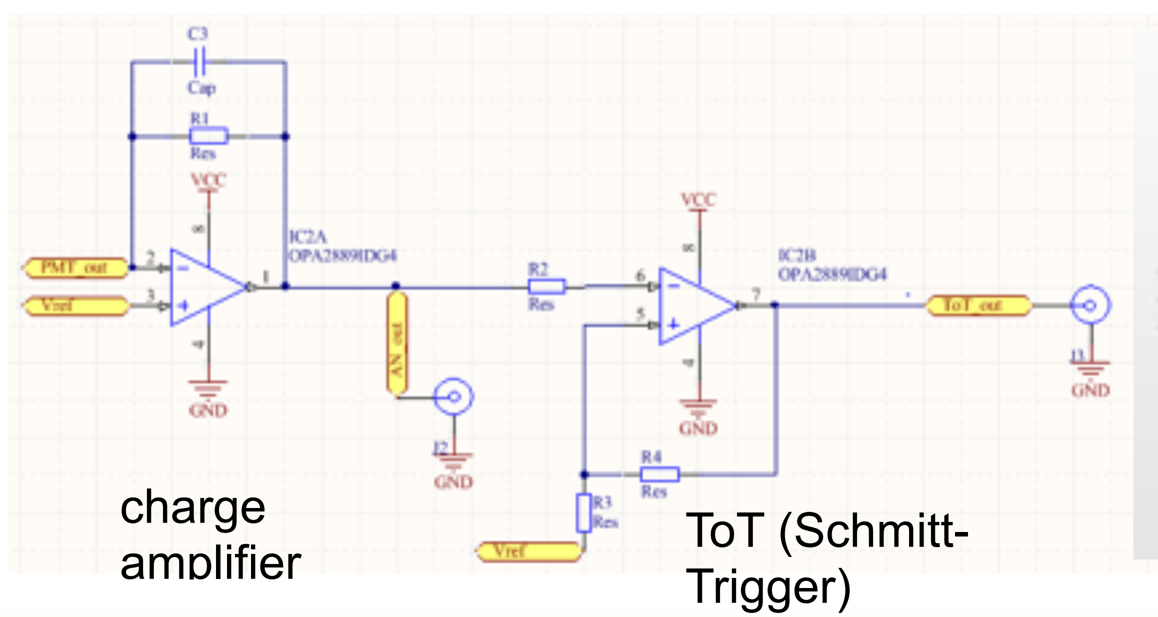
Discrete layout for single ToT readout

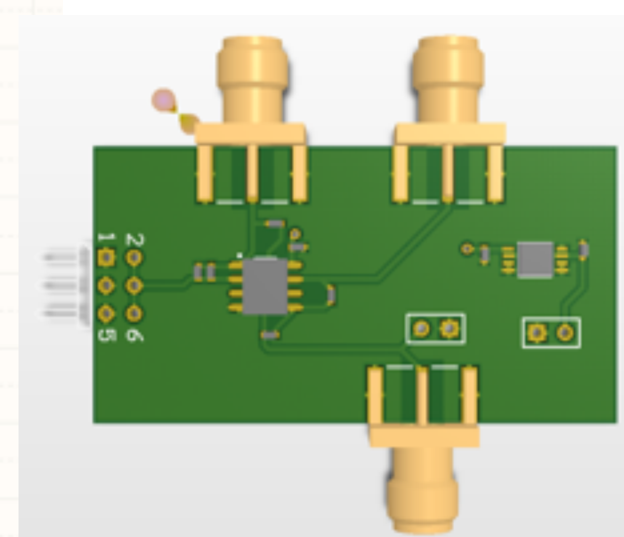
- Low power & tiny footprints
- Micro controller
  - Communication
  - Control of DACs (HV, threshold ToT)
  - PMT-Status
  - Calibration
- Low Power Charge Amplifier & Comparator

Load	Consumption
HV generation	~5 mW
Microcontroller	<< 1 mW
DACs	~10 µW
Charge Amplifier	~5 mW
ToT	~5 mW
Signalling to mainboard	??

Test setup







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Electronics: Baseline readout IceCube mDOM

- 4 ToTs discrete discriminators
- Measured power consumption: ~40 mW per base for 0.001 – 1 MHz toggle rate (expected rates ≲ 0.05 MHz)