WWU MÜNSTER

A multi-PMT optical module for the South Pole

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NEPTUNE Workshop
Naples, 20. July 2018

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Institute for Nuclear Physics

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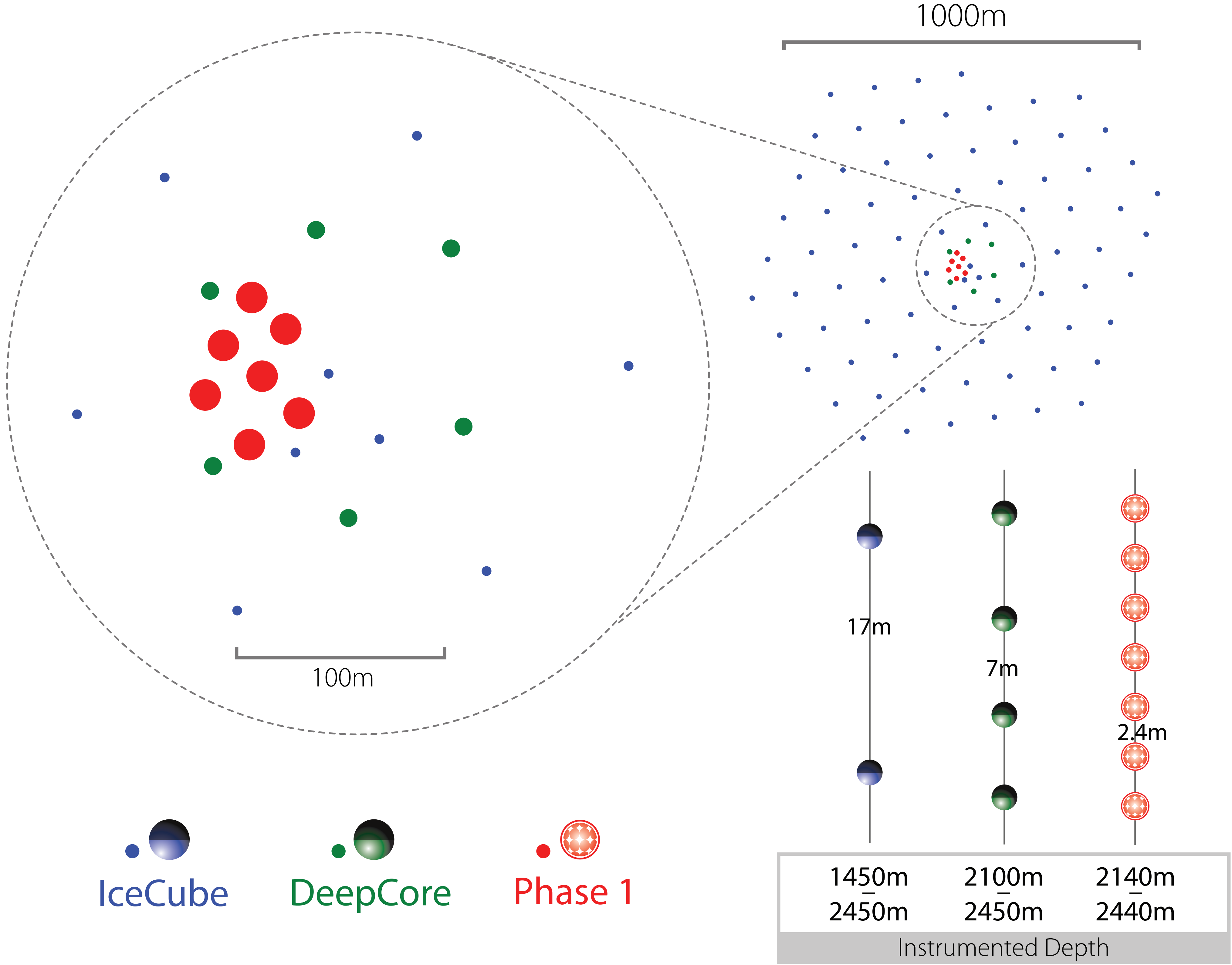
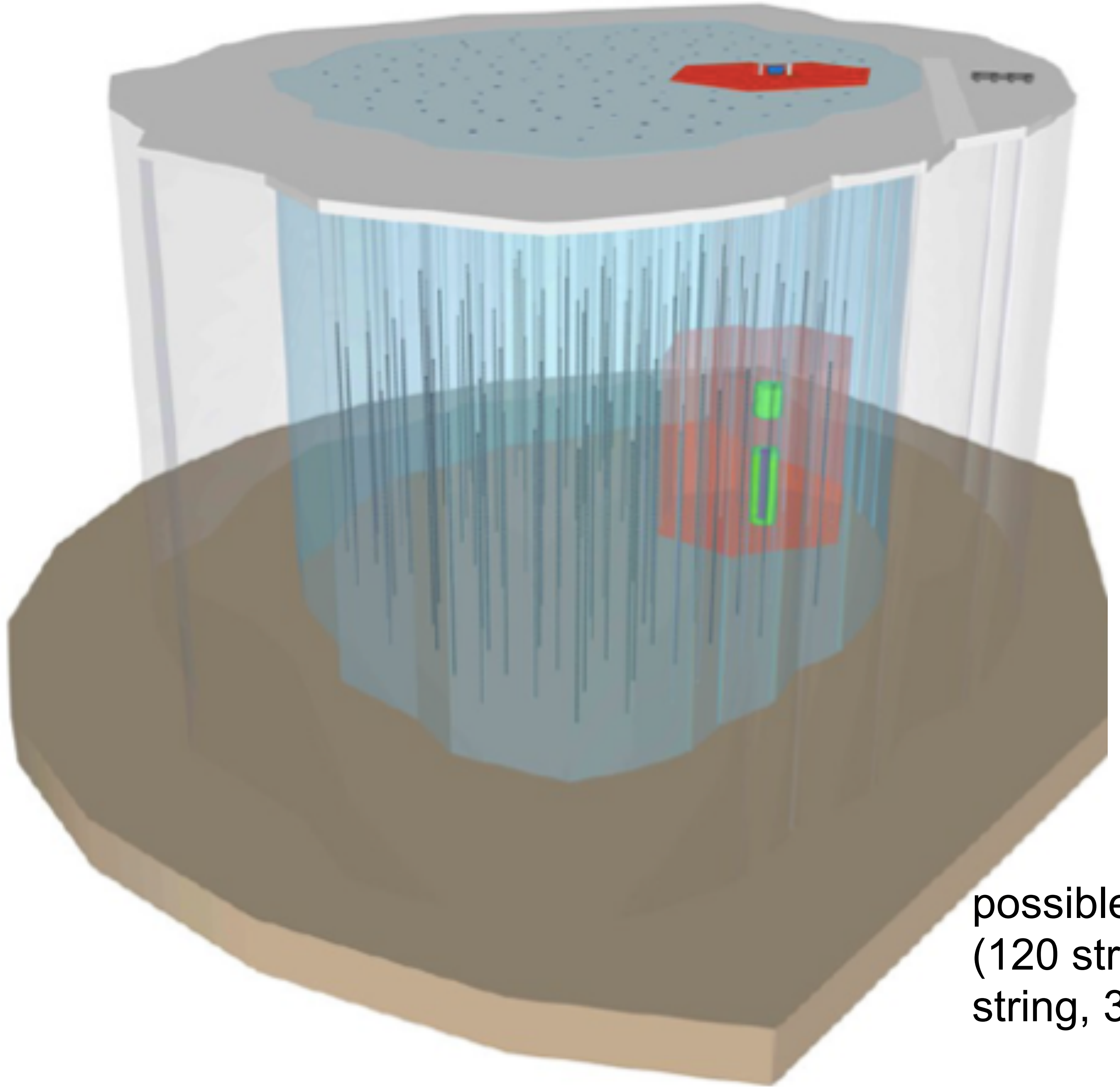
Detector plans for the South Pole

IceCube Upgrade
(7 strings, ~900 modules)

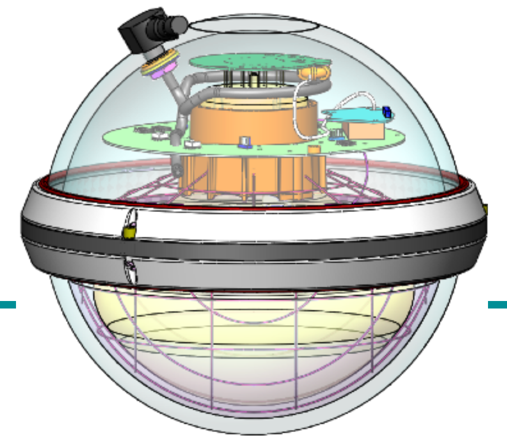


IceCube-Gen2
(120 strings, ~10,000 modules)

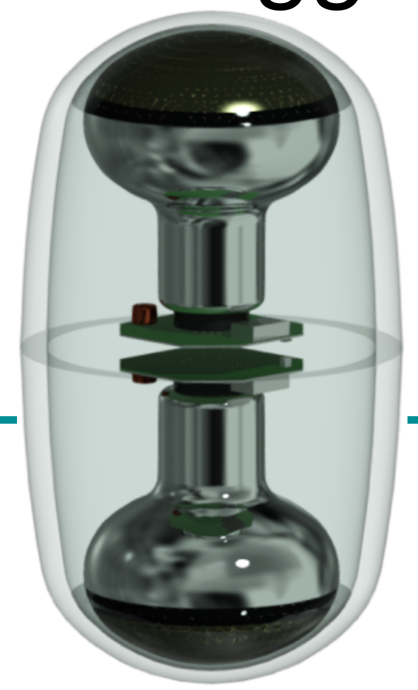


possible configuration (120 strings, 80 DOMs/ string, 300 m spacing)

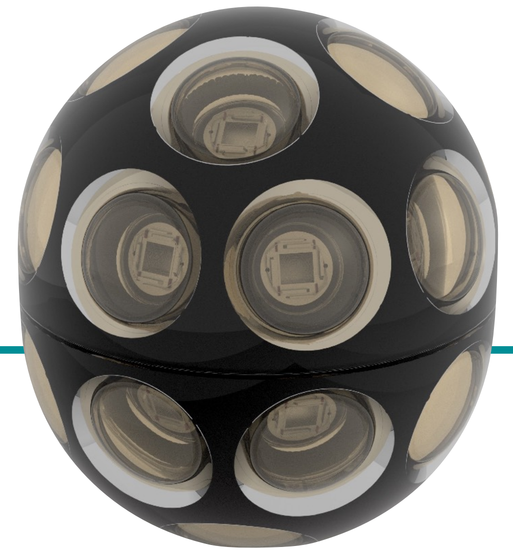
Gen2 DOM



D-Egg



mDOM



WOM

Challenges for optical modules at the South Pole

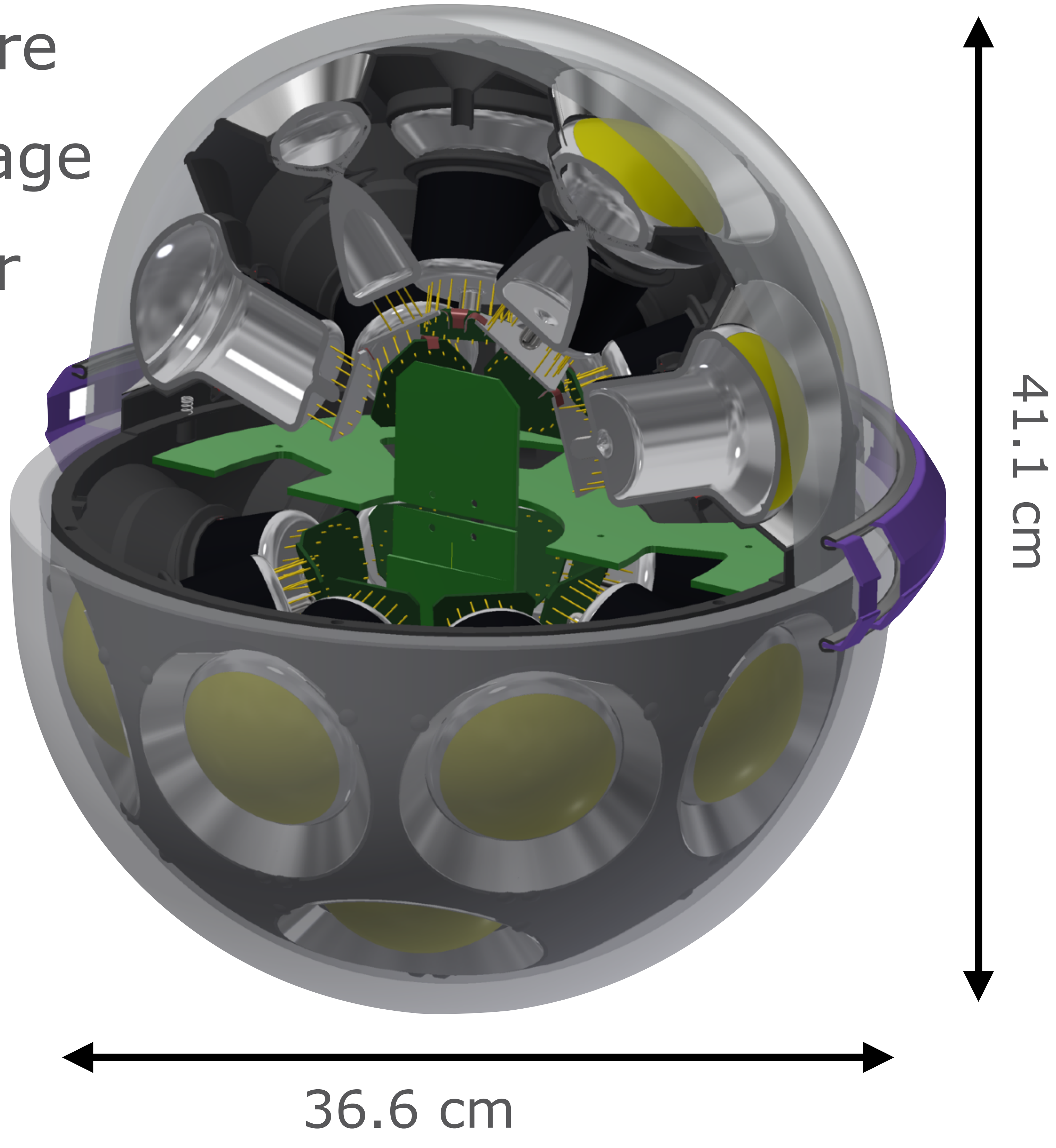
- Have to withstand up to 700 bar pressure during freeze-in
- Have to operate at –40°C
- Tight space constraints inside module
  (outer diameter limited to < 14” by max. bore hole diameter)
- Tight power constraints (< 3—4 W per module)
- Limited data bandwidth (copper cables for data transfer)
- High reliability over >10 years (no repairs possible)

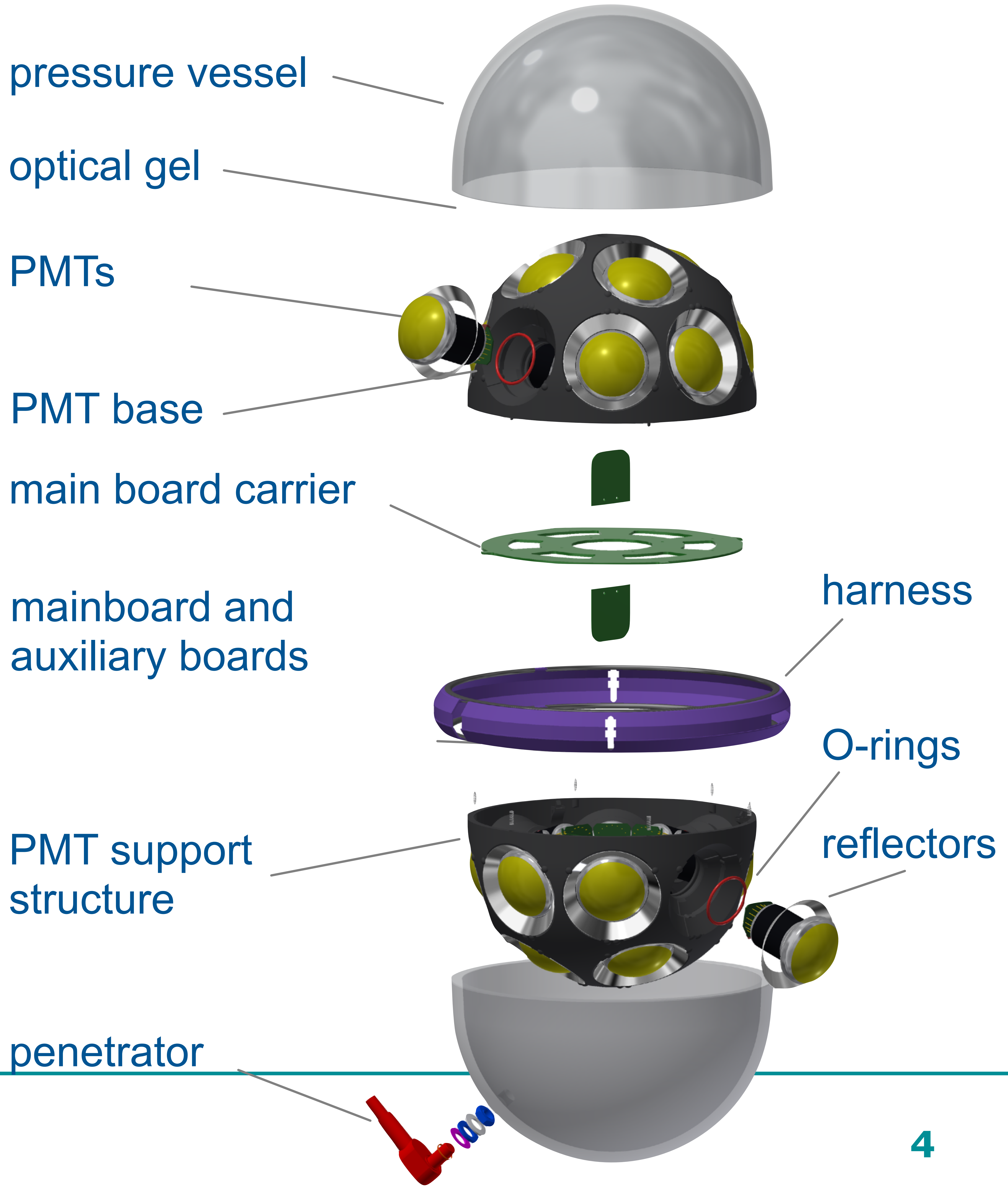
mDOM overview

mDOM baseline option for IceCube-Upgrade

Advantages of multi-PMT optical modules

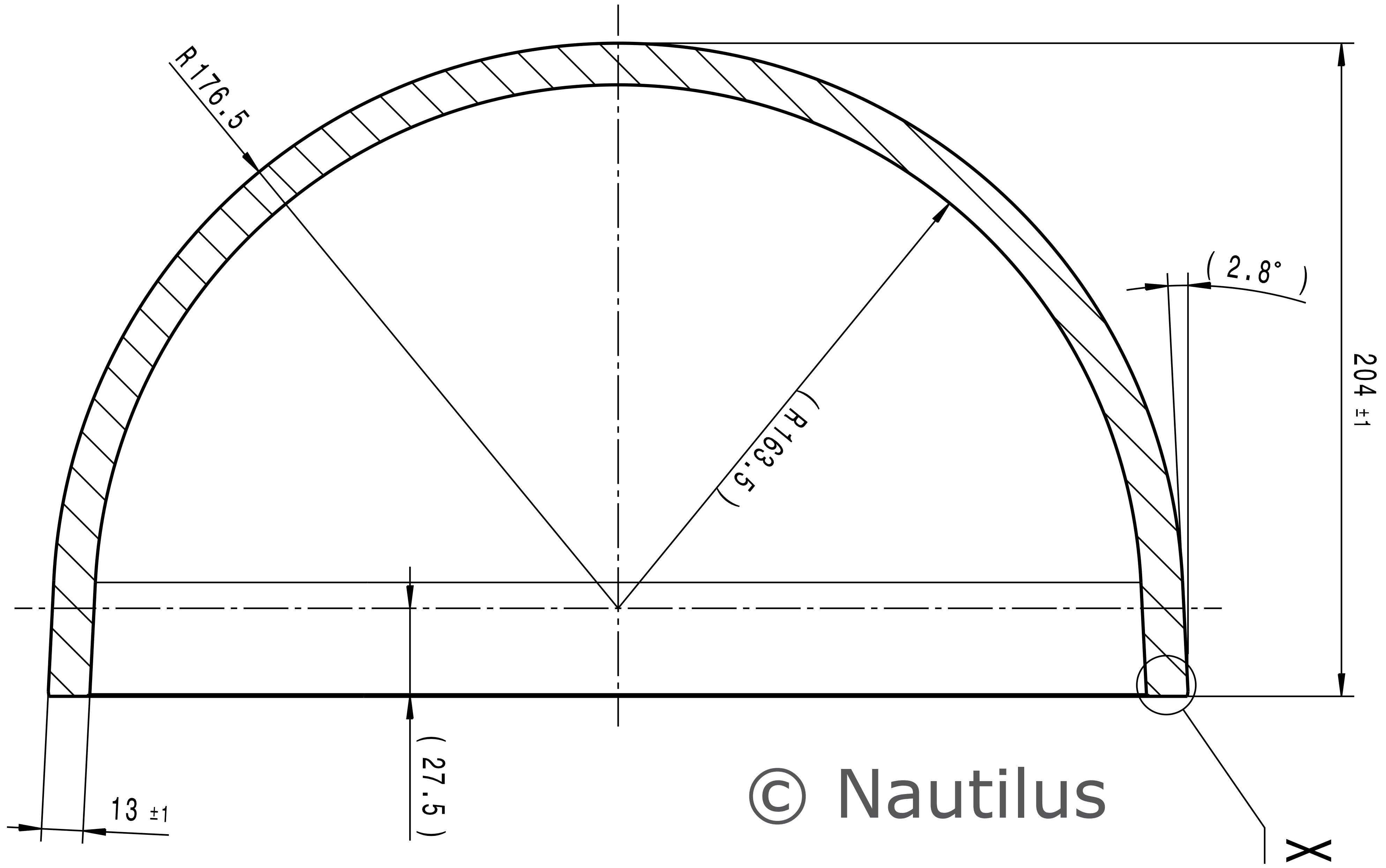
- increased photocathode are
- uniform solid angle coverage
- local coincidences, e.g. for background suppression
- information on photon arrival direction
- improved photon counting



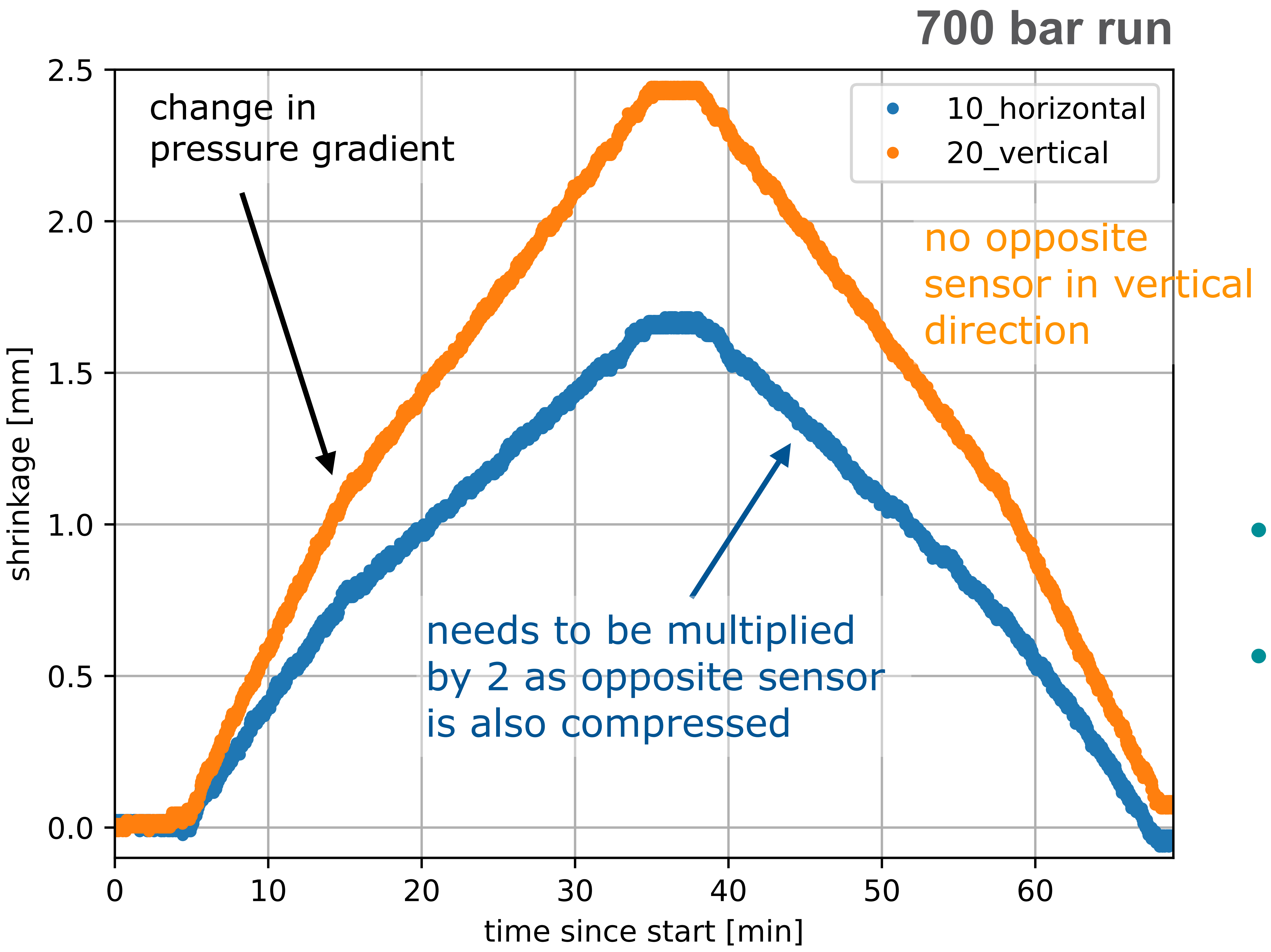


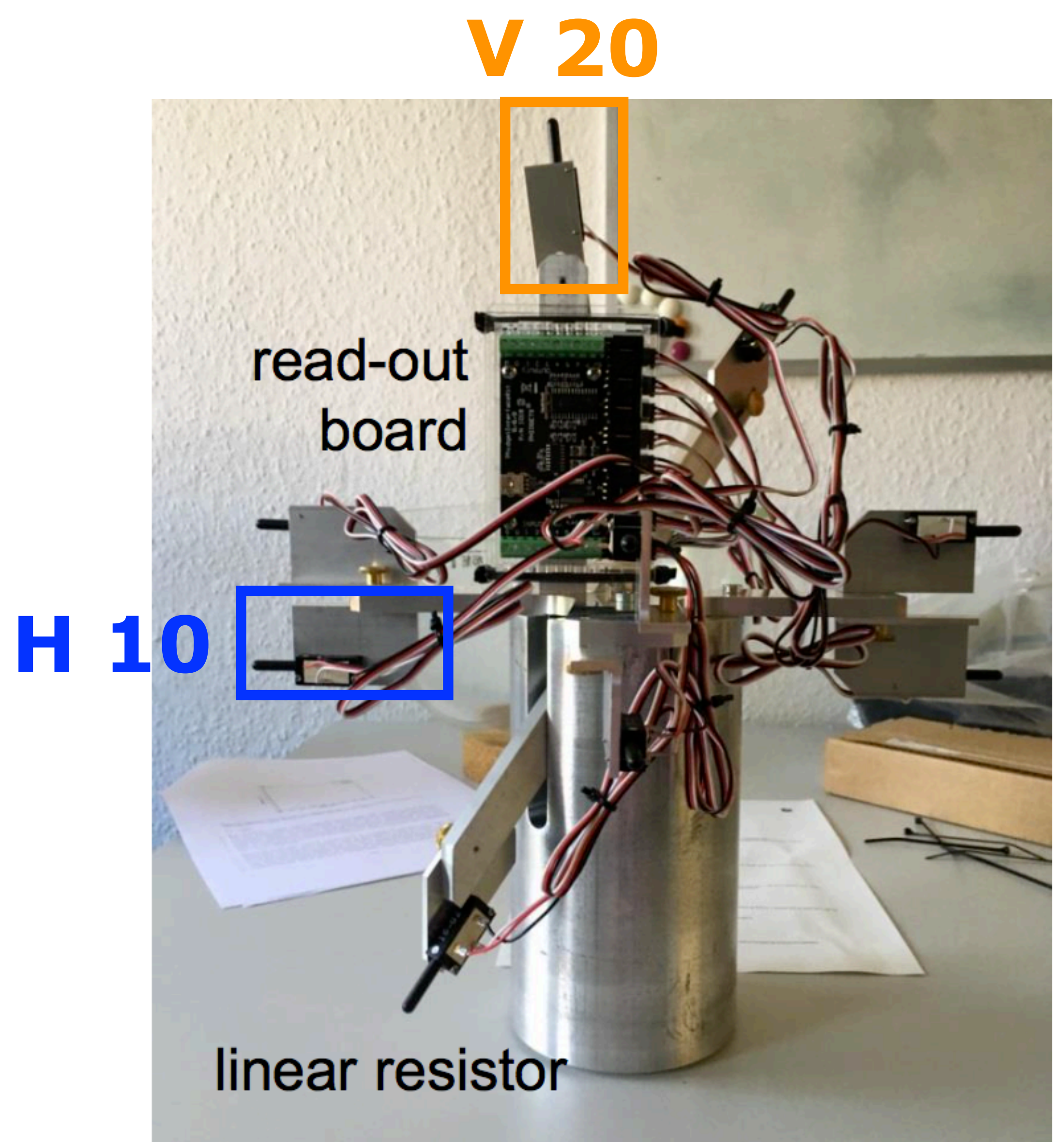
Pressure vessel

- Two spherical half vessels with 14” diameter and 27.5mm cylindrical extension at equator
  - Glass type: borosilicate glass (total weight 13 kg)
  - Glass thickness: 14 mm
- Developed and manufactured by Nautilus



Pressure vessel — pressure tests



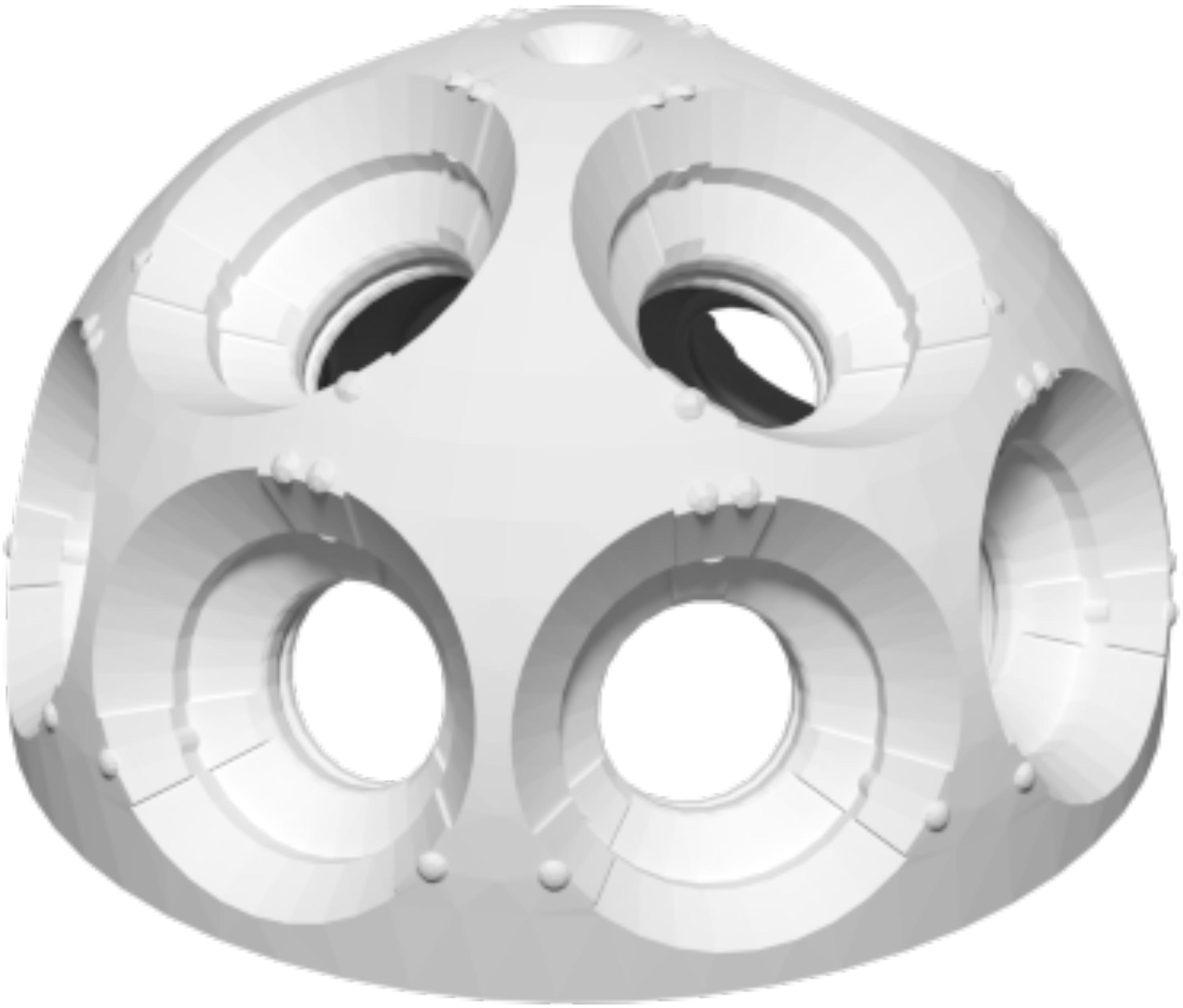


- Deformation is reversible and follows external pressure linearly
- Maximal deformation agrees well with calculations using Lamé formula at 700 bar
  - spherical vessel: 2.0 mm on diameter expected → 2.5 mm measured
  - cylindrical vessel: 4.6 mm on diameter expected → 3.2 mm measured

PMT support structure (I)

Currently 3d printed from polyamide via laser sintering

- Advantages
  - allows realization of complex structures
  - modifications possible on short timescales
- Disadvantages
  - expensive in mass production (~400 EUR per half)
  - long production time (~2 days including cooling)
    → production capacity sufficient?

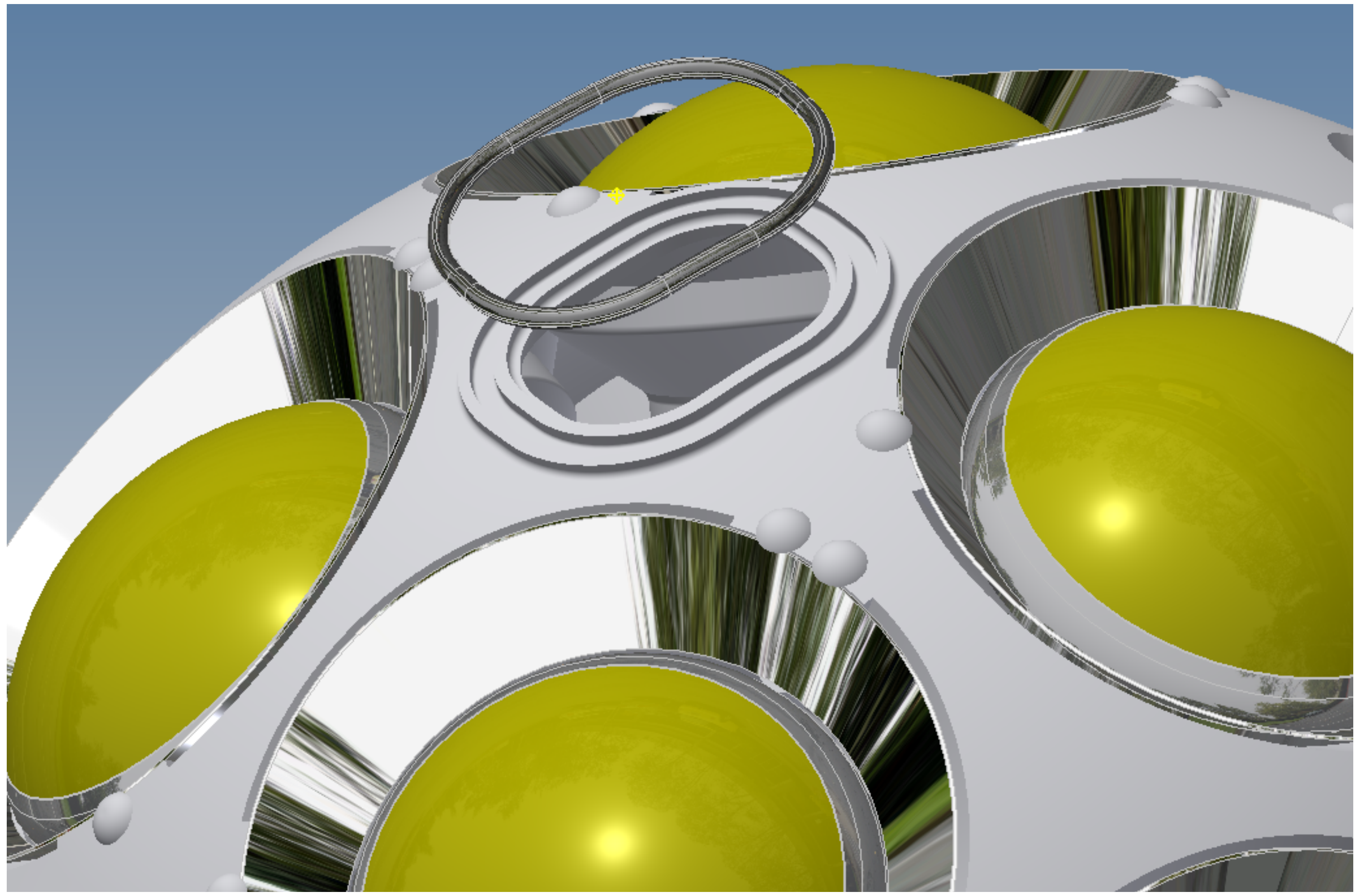


Alternative: Injection molding

- Disadvantages
  - half-sphere structure and PMT cups have to be produced separately and assembled afterwards
  - price for tools high (~70 kEUR)
- Advantages
  - Low price for large quantities
  - Much higher production capacity

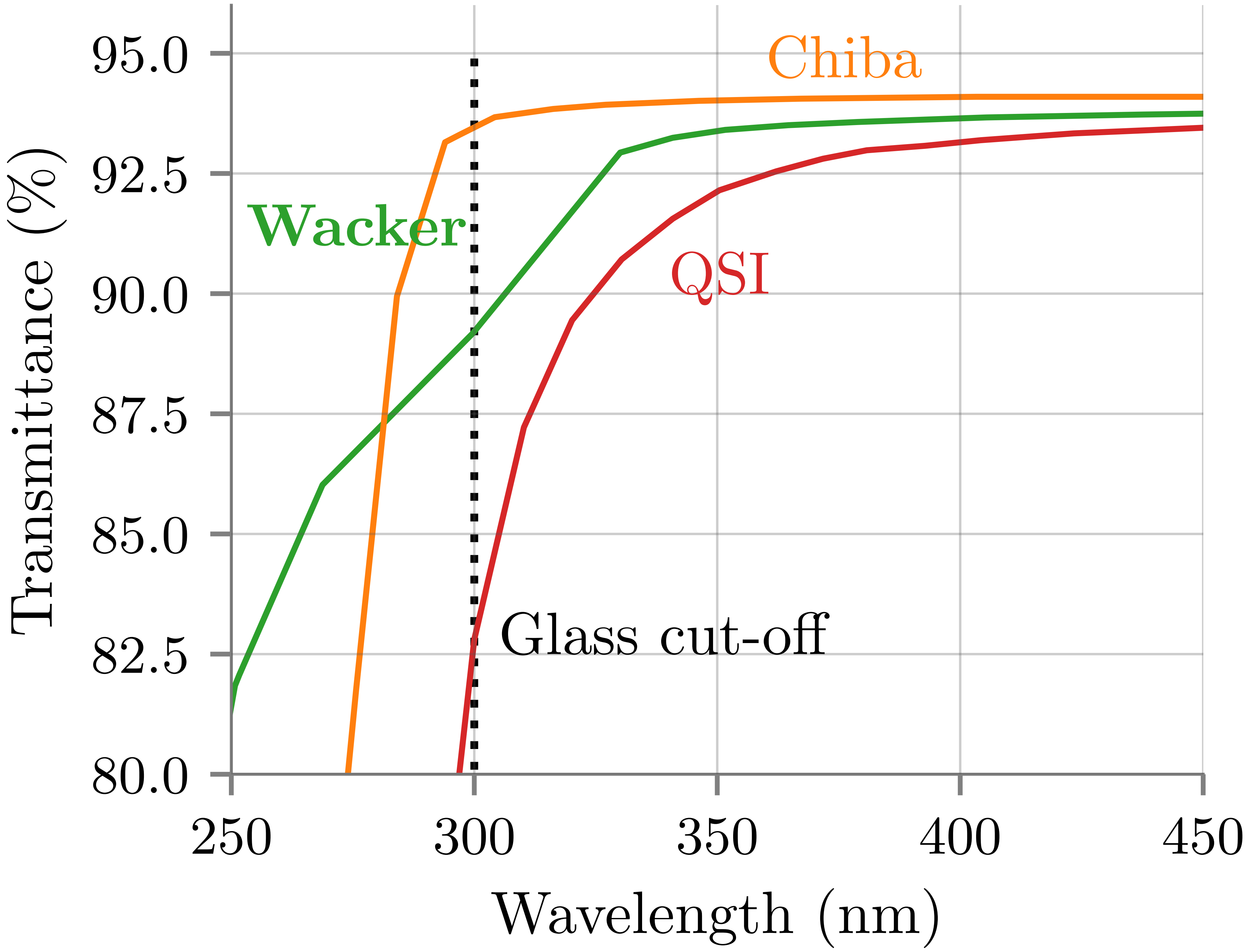
PMT support structure (II)

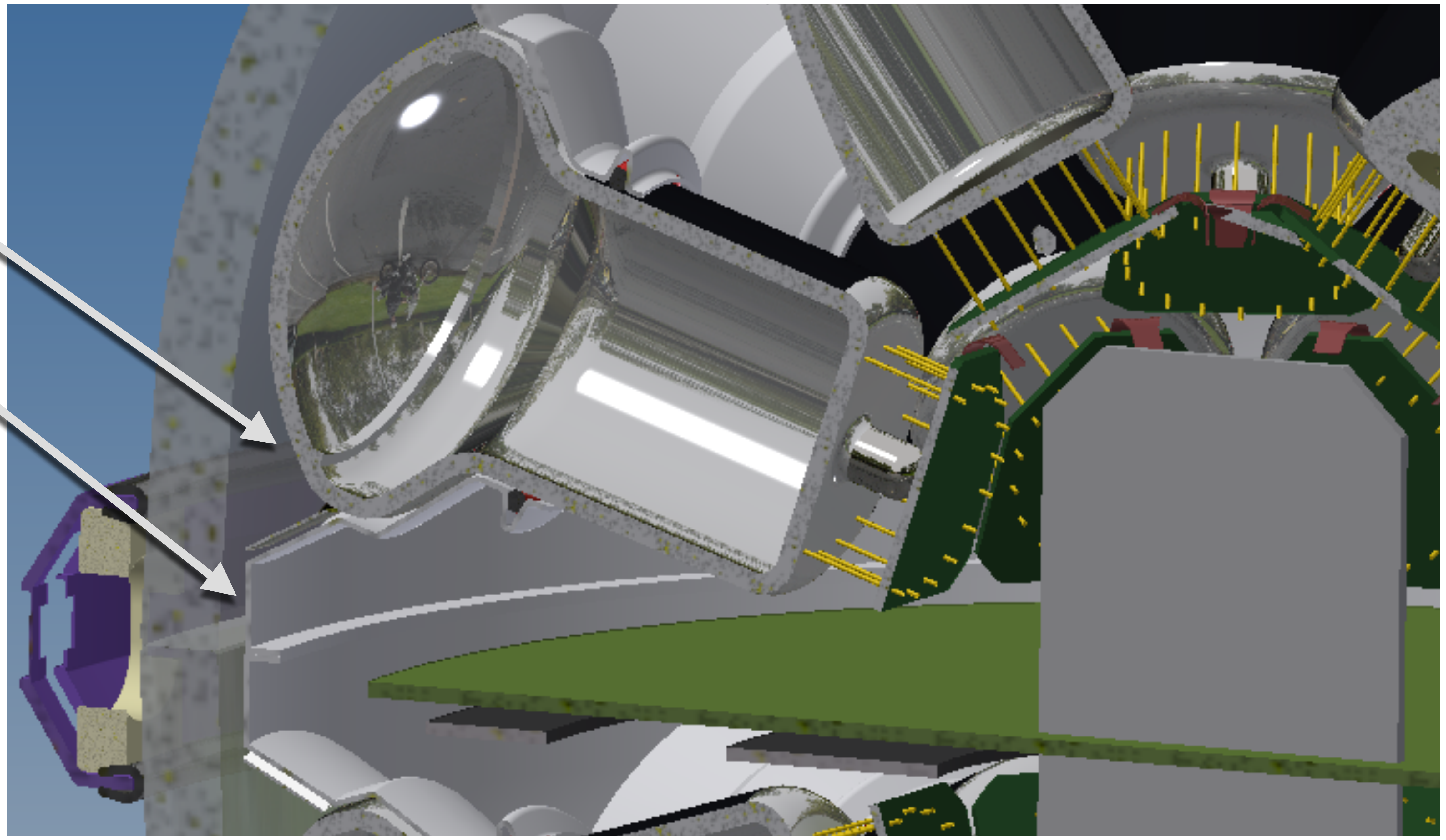
- Weight of upper PMTs pulls on PMT support structure
  → spring mechanisms to counteract gel detachment
- Hole for penetrator needs to be sealed against optical gel
  → O-ring on support structure surface (needs to be tested)



Optical gel

- Fills gap between PMT support structure / PMTs and pressure vessel
- Transmission properties vary significantly between brands

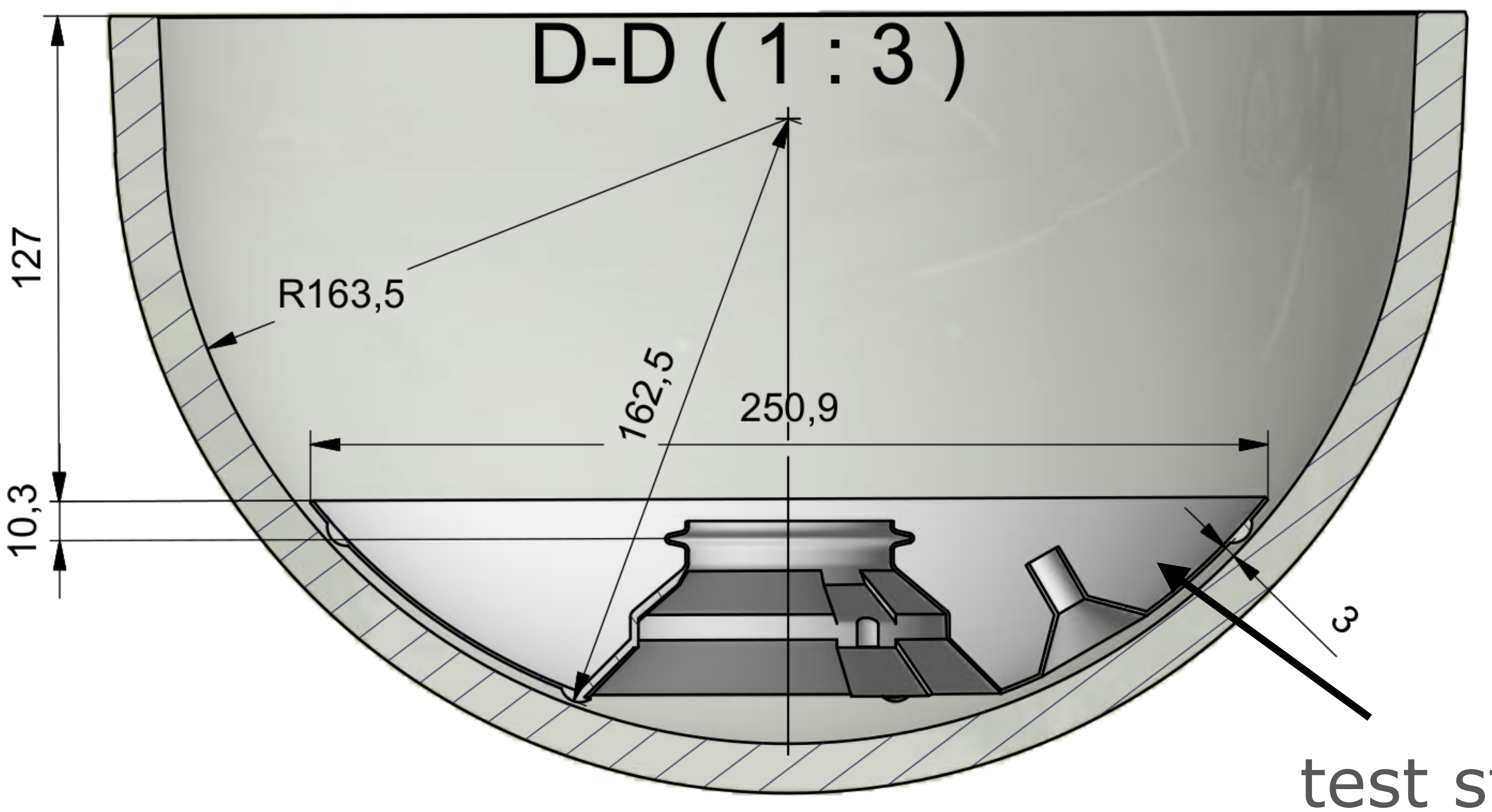




- Initially Wacker SilGel 612 → crystallizes at −45°C into a hard and opaque state
- Switched to QGel 900 from QSI (gel used in IceCube DOMs)

Optical gel — detachment tests

- Upper half of PMT support structure pulls with about 1.5 kg (PMTs + bases) at gel (part of force will be compensated by springs between vessel halves)
  - pulling with 2 kg at test support structure over several days shows no indication of detachment
  - tests with closed vessel under pressure will follow



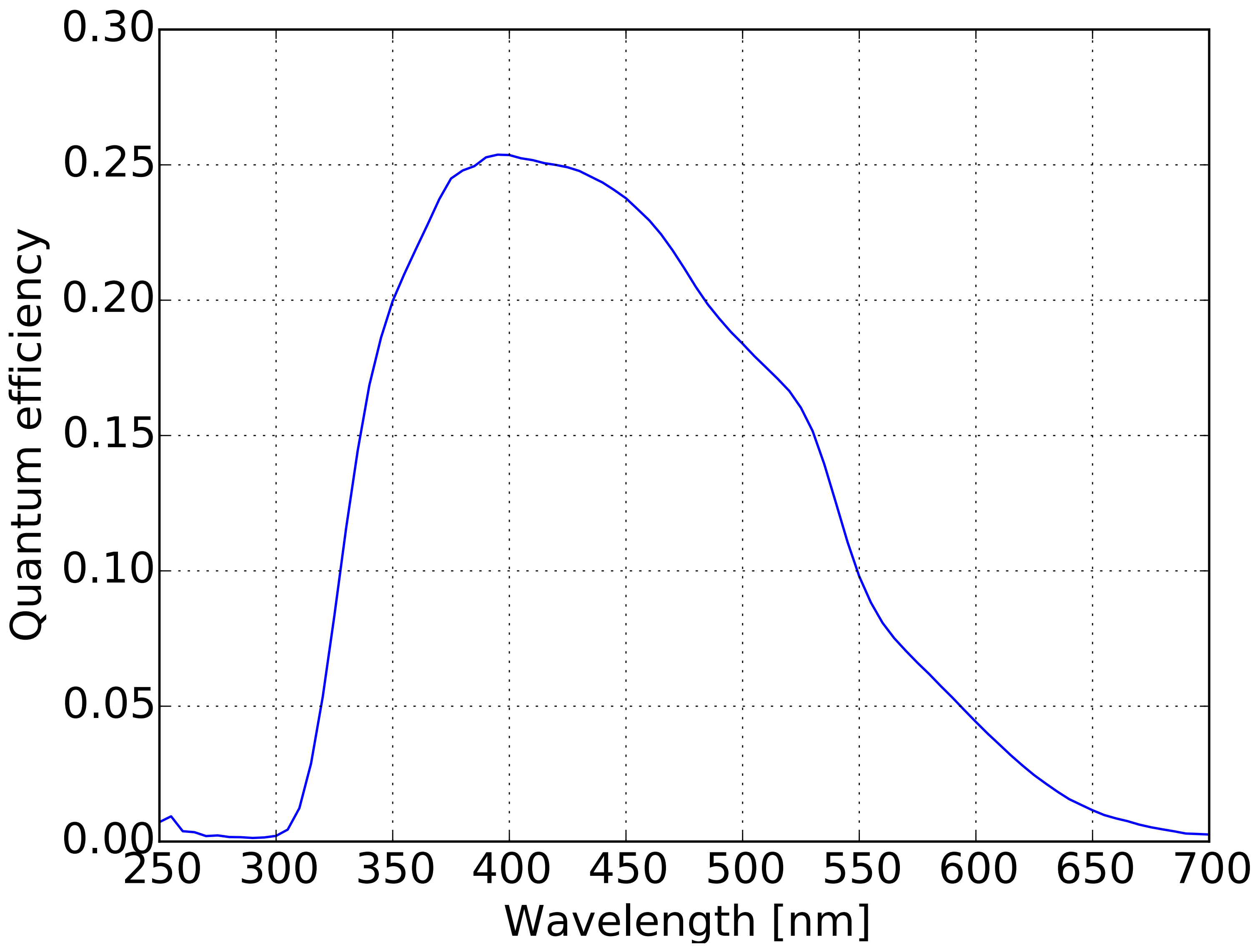
test structure

Photomultiplier

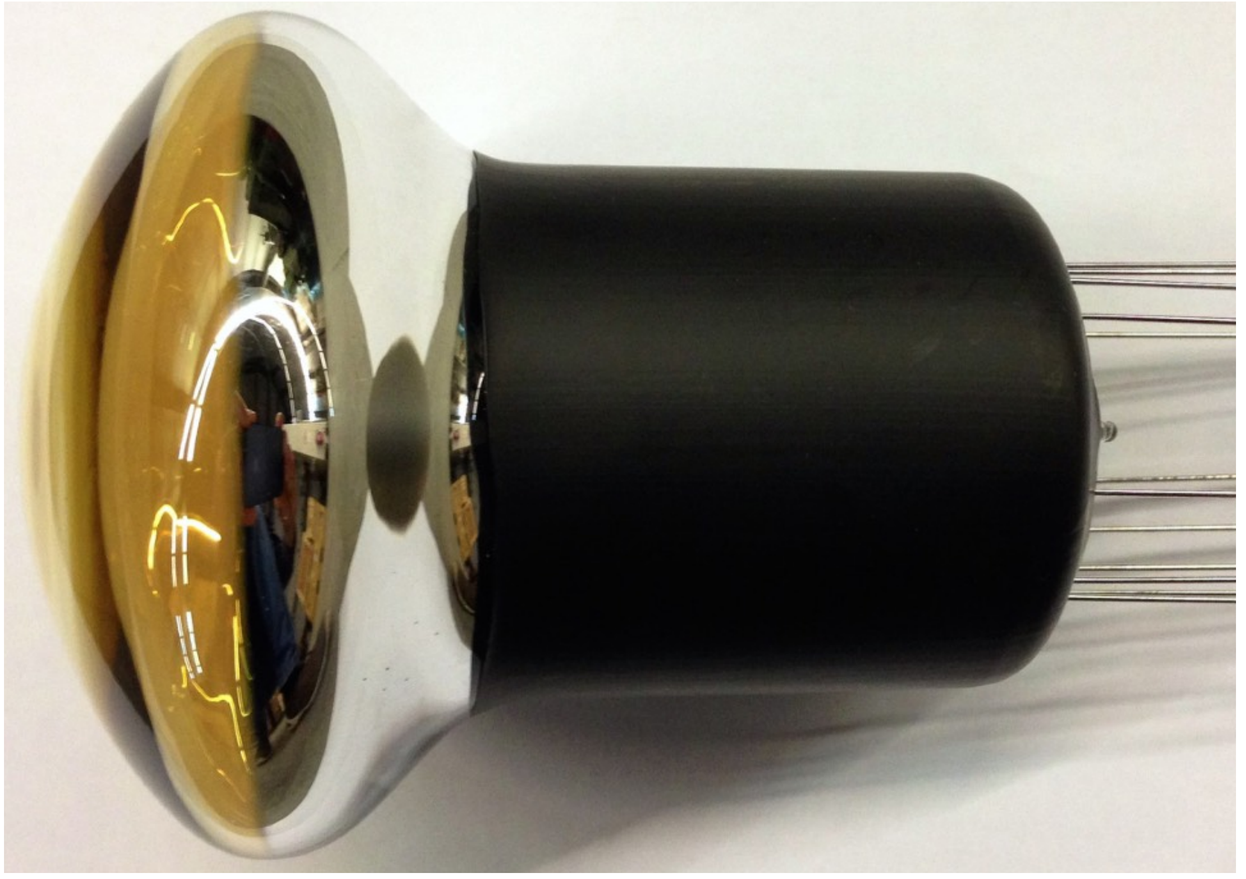
Plan to operate with negative HV at photocathode

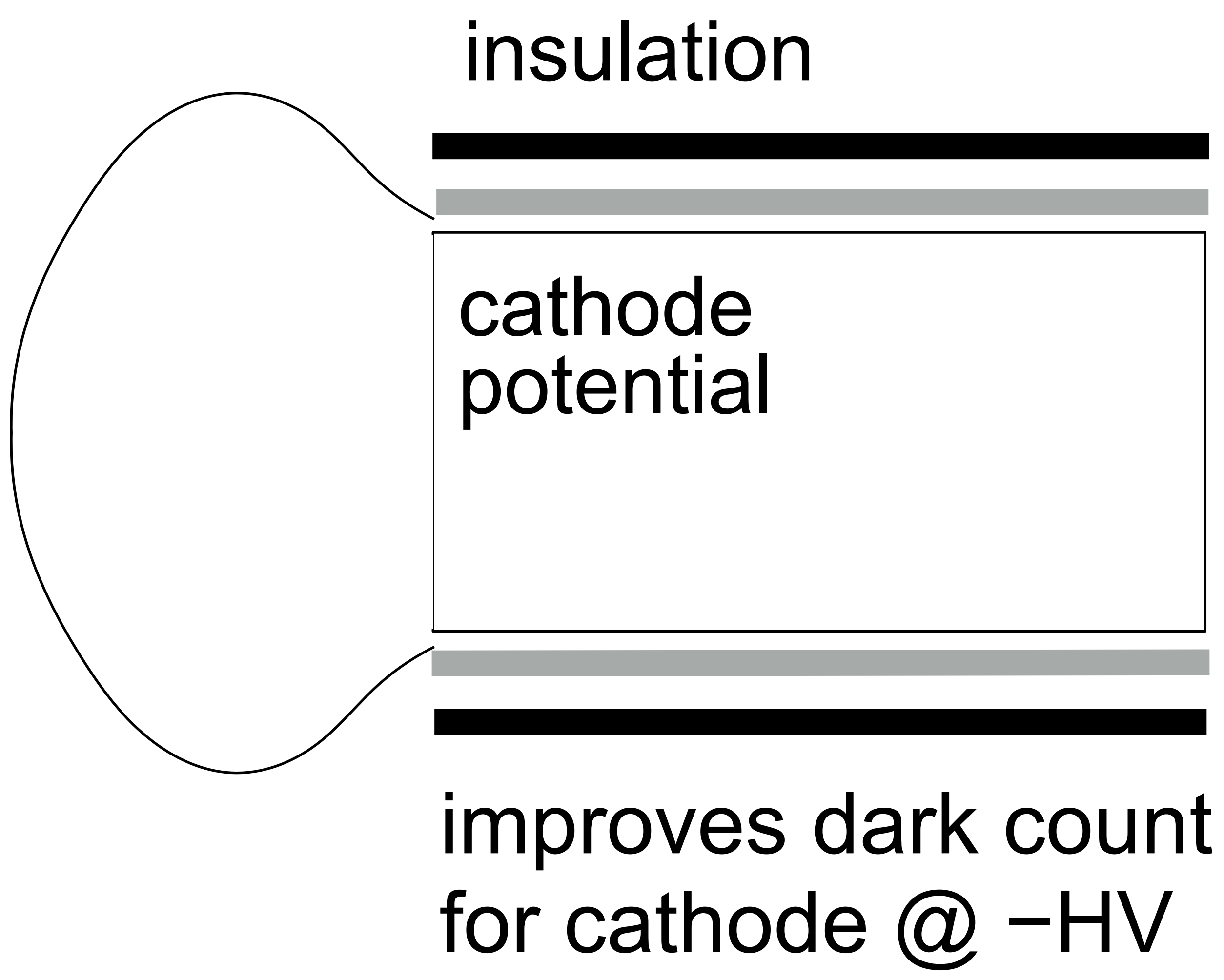
For prototype development: Hamamatsu 12199-02 HA MOD

- Modified version which is 5 mm shorter and has HA coating
- HA coating puts glass outside photocathode area on HV thereby reducing dark-noise rate due to electrons hitting glas from inside
- PMT characteristics
  - diameter 80 mm (cathode >72 mm)
  - length 93mm
  - gain ~3×10⁶ @ ~900 V
  - TTS (FWHM) = ~3.5 ns
  - typical quantum efficiency curve (25% @ 400 nm)
- Alternative (3.5”) PMTs under consideration (HZC, ETEL)



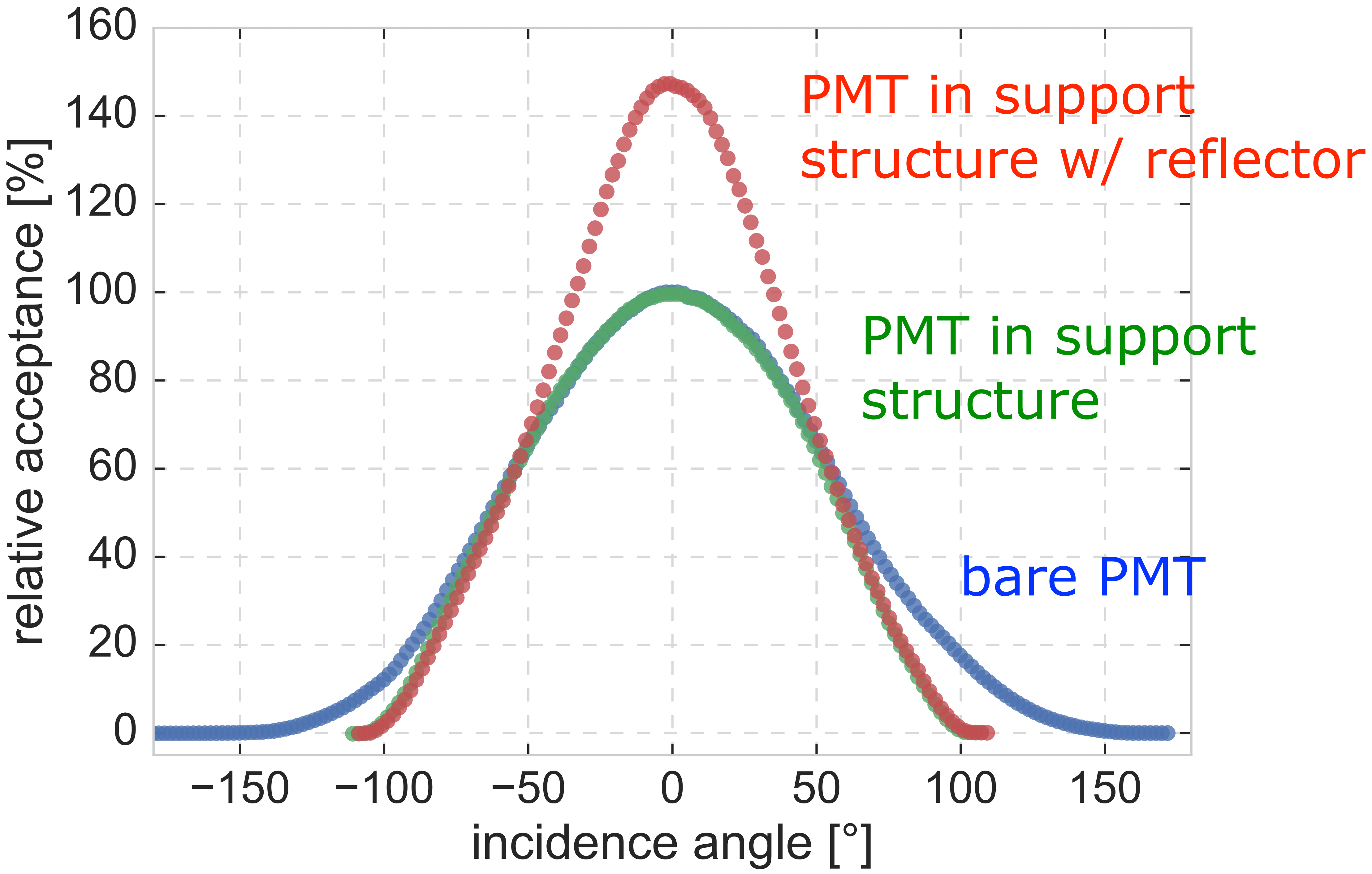
Hamamatsu R12199-02 HA



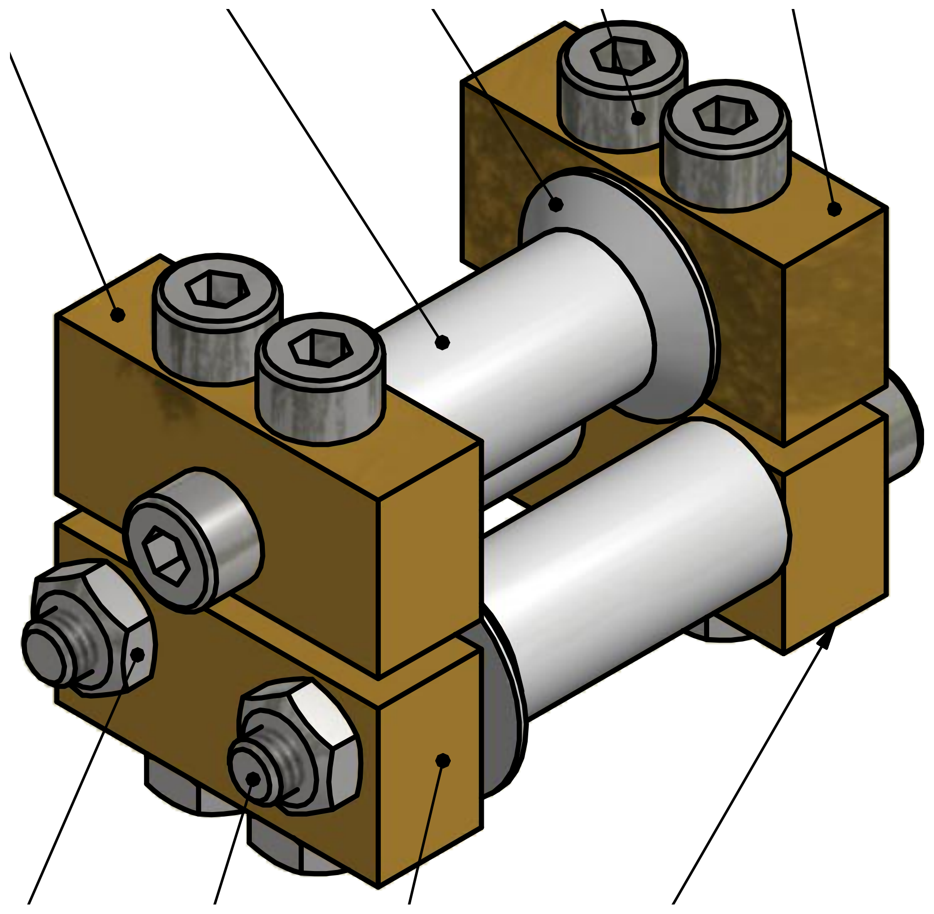


Reflectors

- Reflector increases photon-collection area and directionality
- Laser-cut from coated aluminum sheet (Almeco V95)
- Bent by simple hand-held device



Reflector with PMT in test support structure



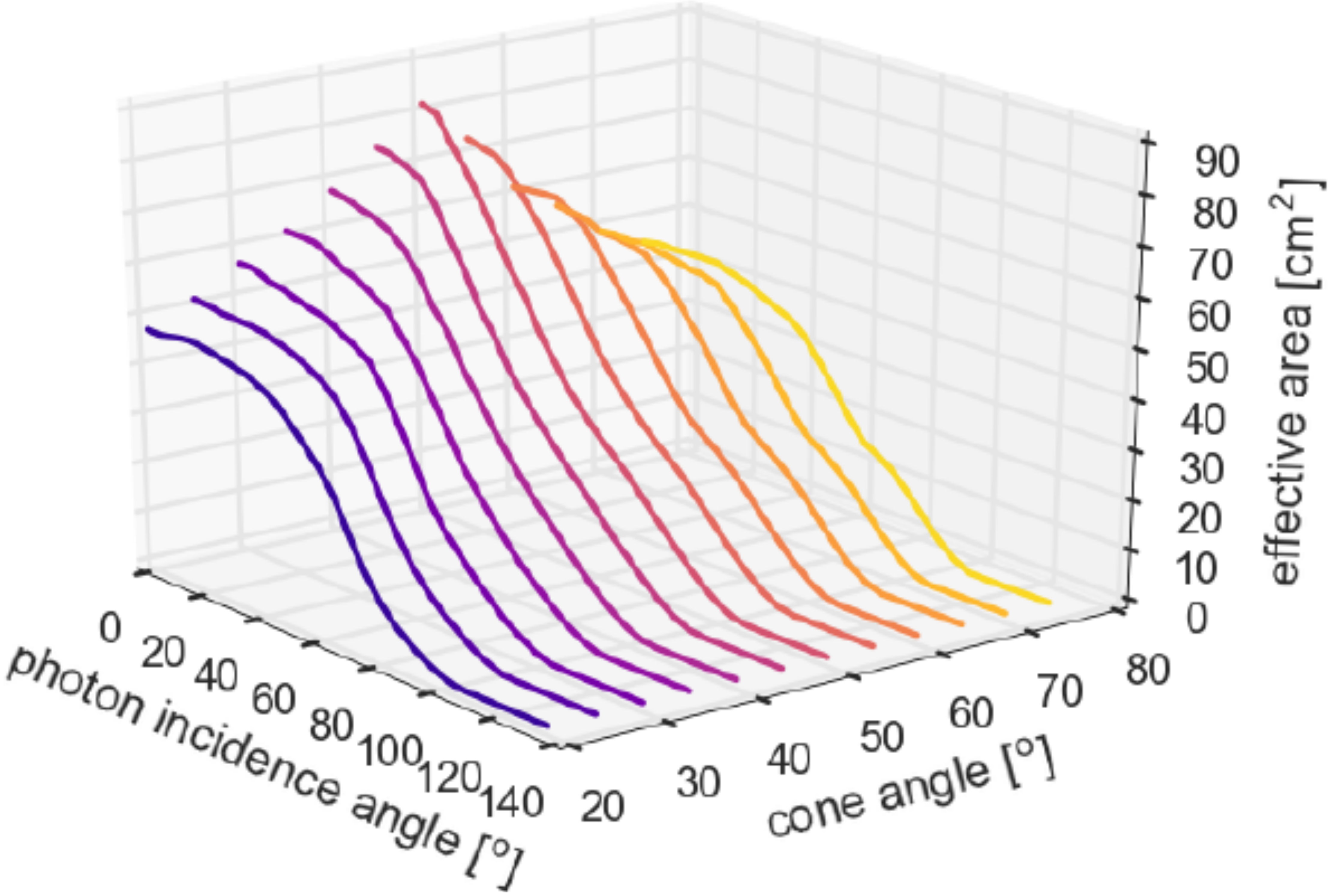
Bending tool

Bended reflector

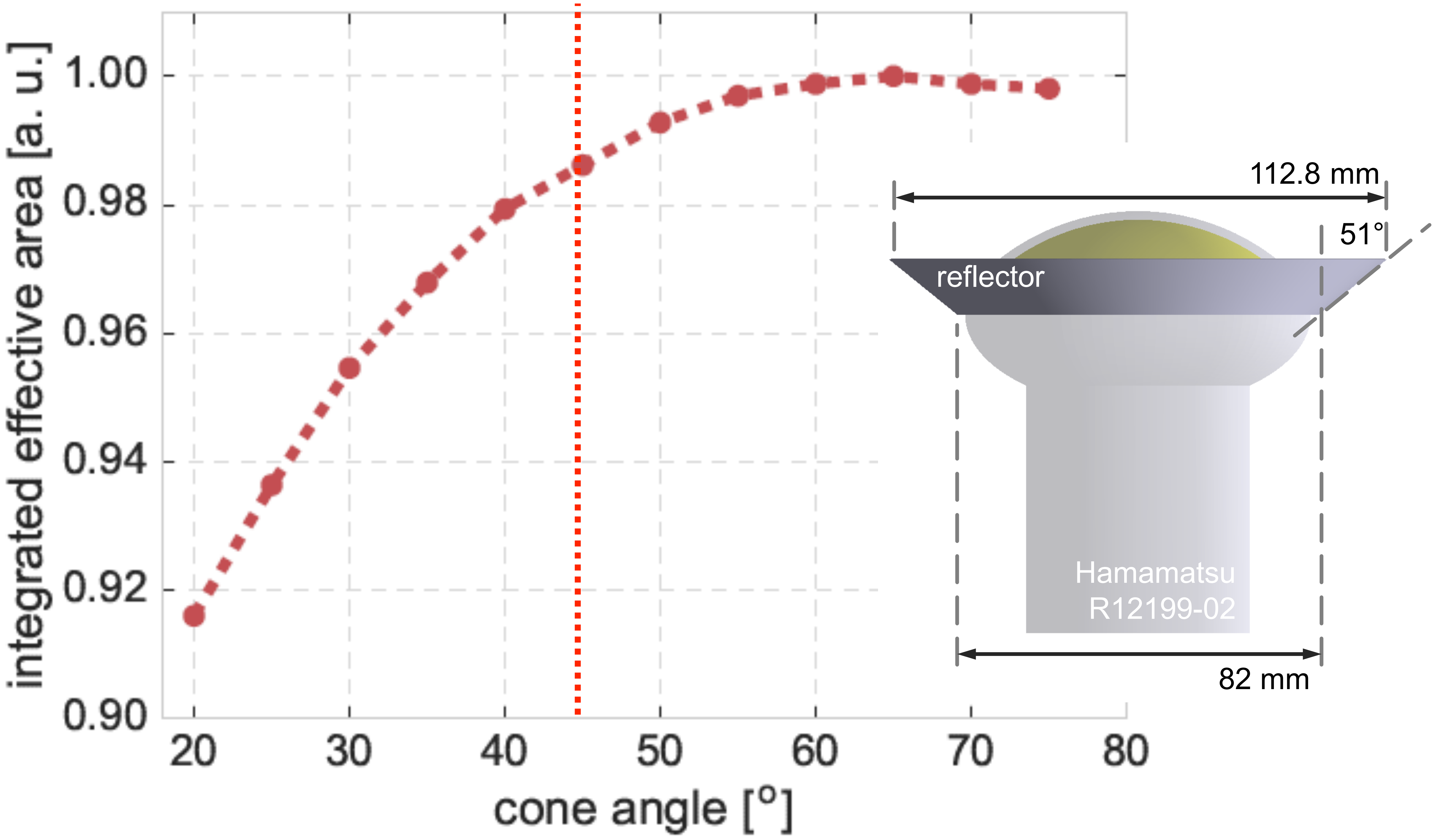
Reflector-angle optimization

- Optimal directional sensitivity for reflector angle of 51° from GEANT4 simulation (currently using 45° to increase spacing between reflectors)

GEANT4 simulation



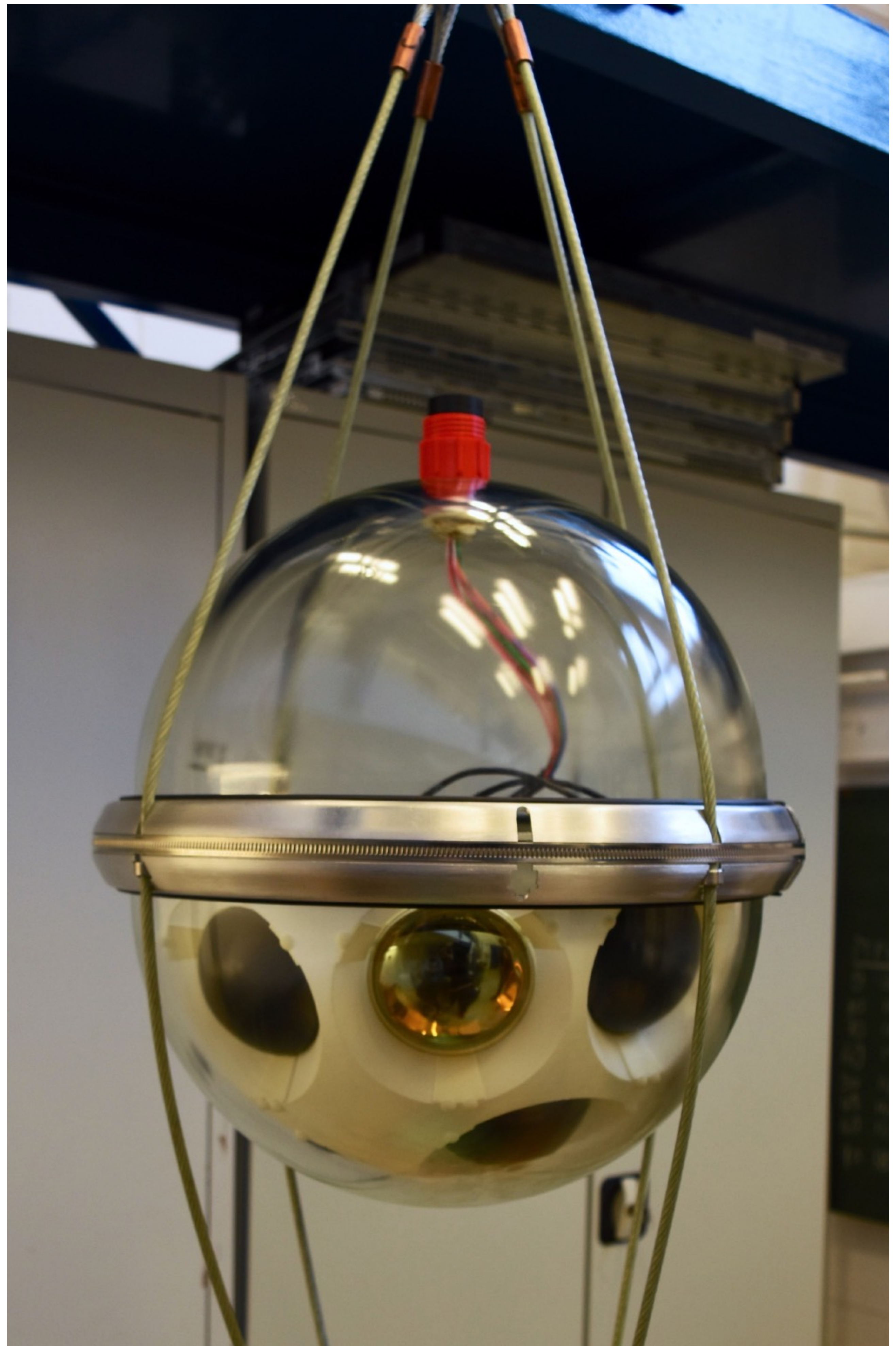
current angle

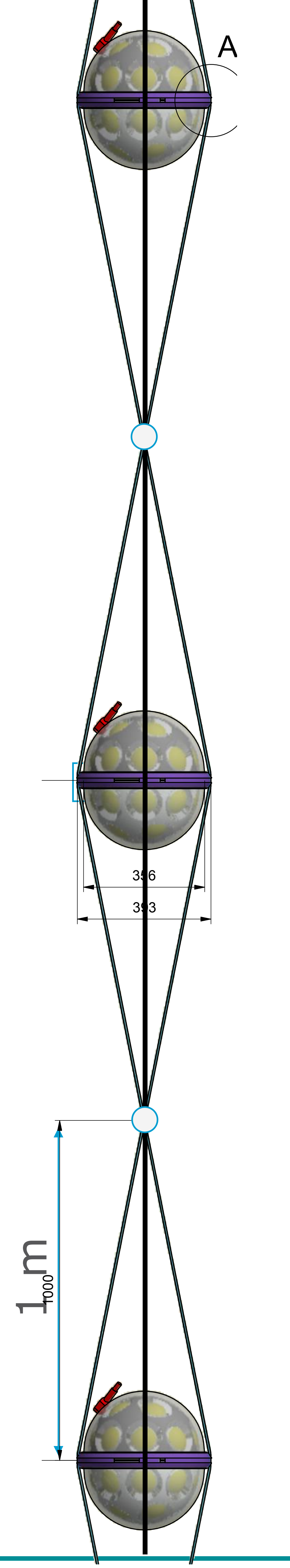


Harness design

Based on proven IceCube design

- Major differences
  - 4 cables instead of 3
  - narrower waistband (45 mm vs. 64 mm)
- Prototype available for initial tests

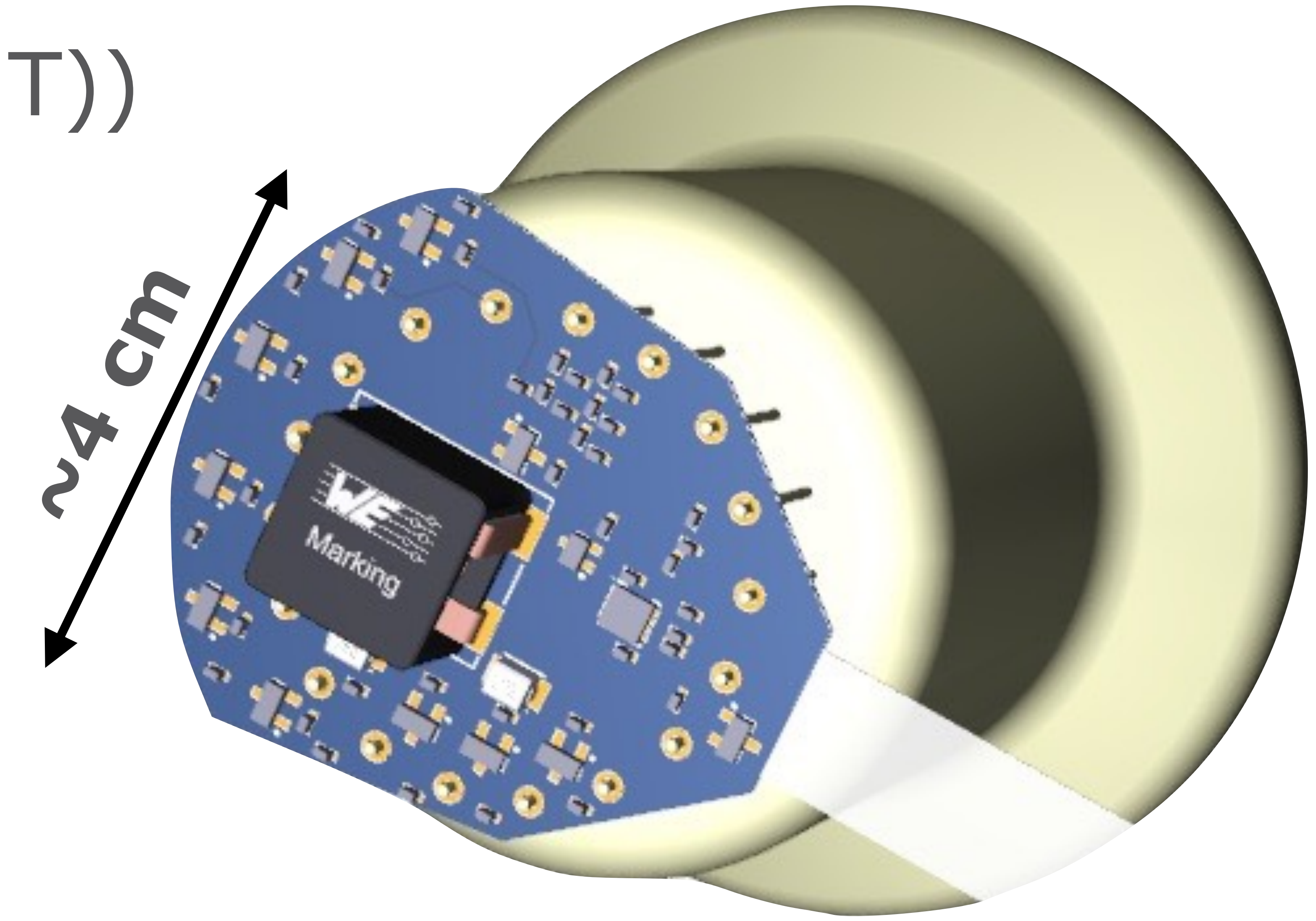




Electronics

General requirements /constraints for readout and HV

- Sampling of also complex (not scaled single pe) PMT waveforms
- Low power consumption (total ≲ 60 mW per channel (PMT))
- Low sensitivity to interference signals (cross talk)
- Low footprint if placed on PMT base
- High reliability



Remark: modular design of common electronics components (communication, timing calibration etc.) with well-defined interfaces
→ used in all module designs together with module-specific components

HV generation — Cockcroft-Walton base

Generation of HV on PMT base via Cockcroft-Walton circuitry
(based on design by Nikhef for KM3NeT, low power consumption)

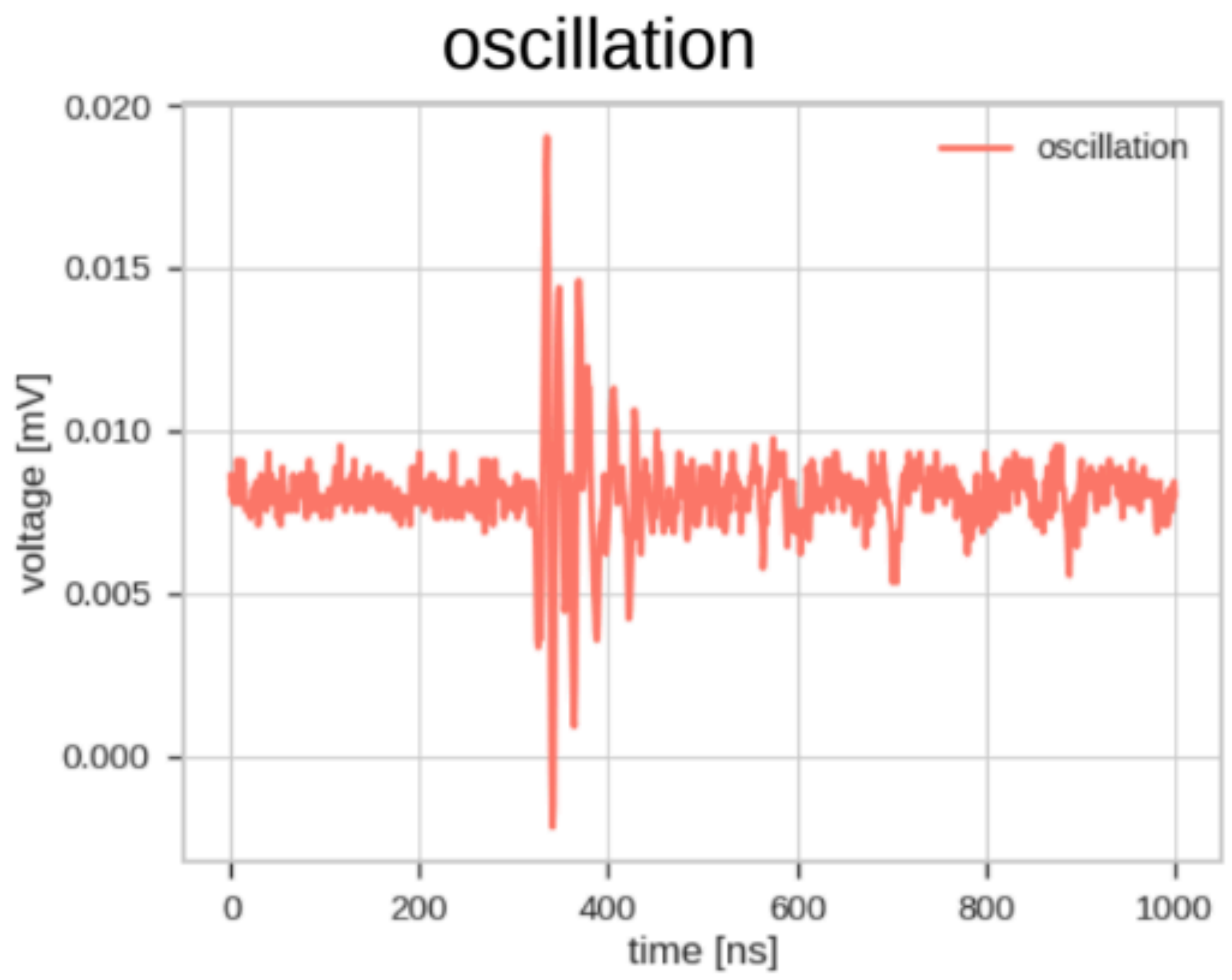
Design specifications

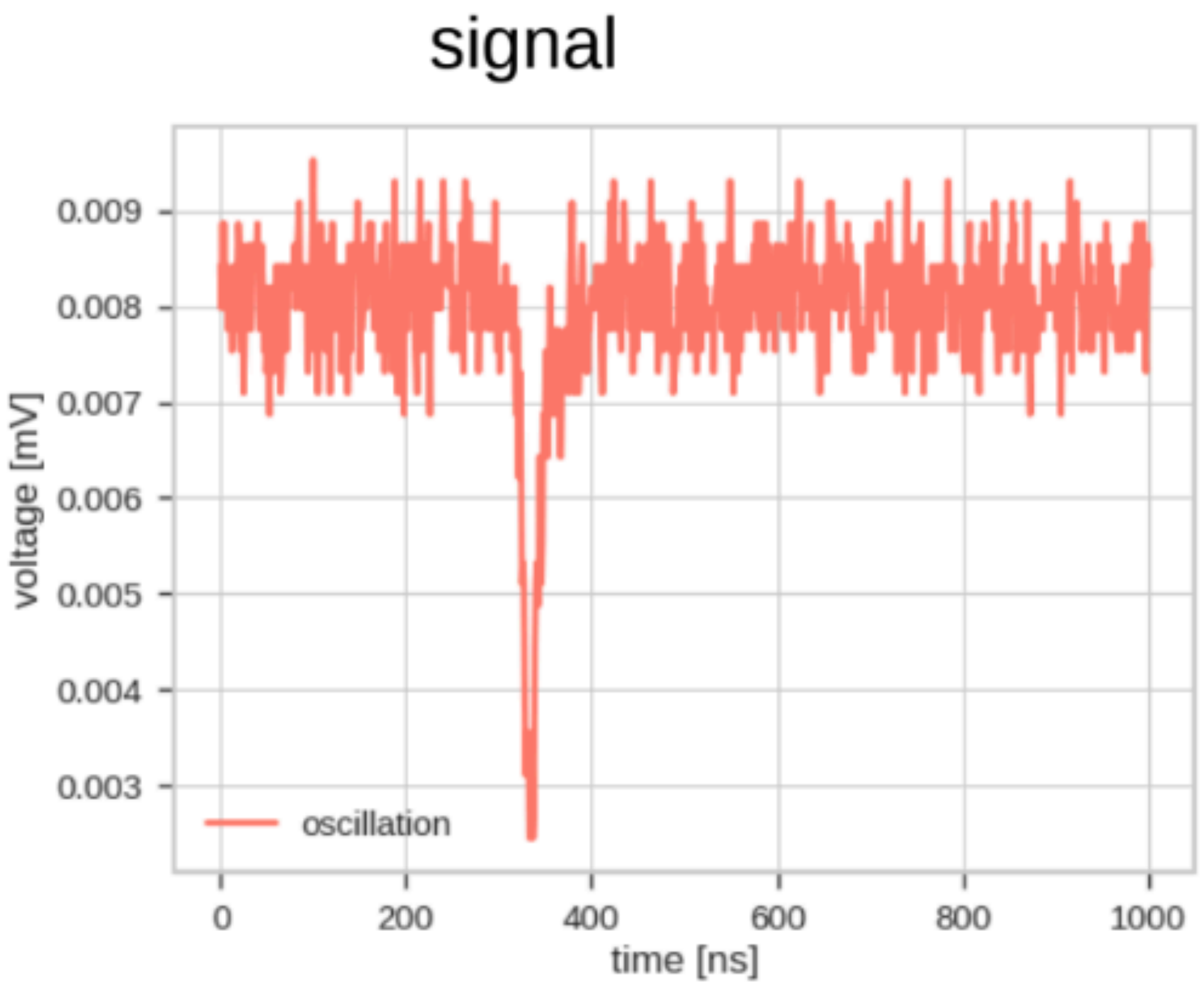
- Power consumption < 4mW
- Output linearity up to 200 p.e.

LTE University Erlangen-Nürnberg

Tests reveal

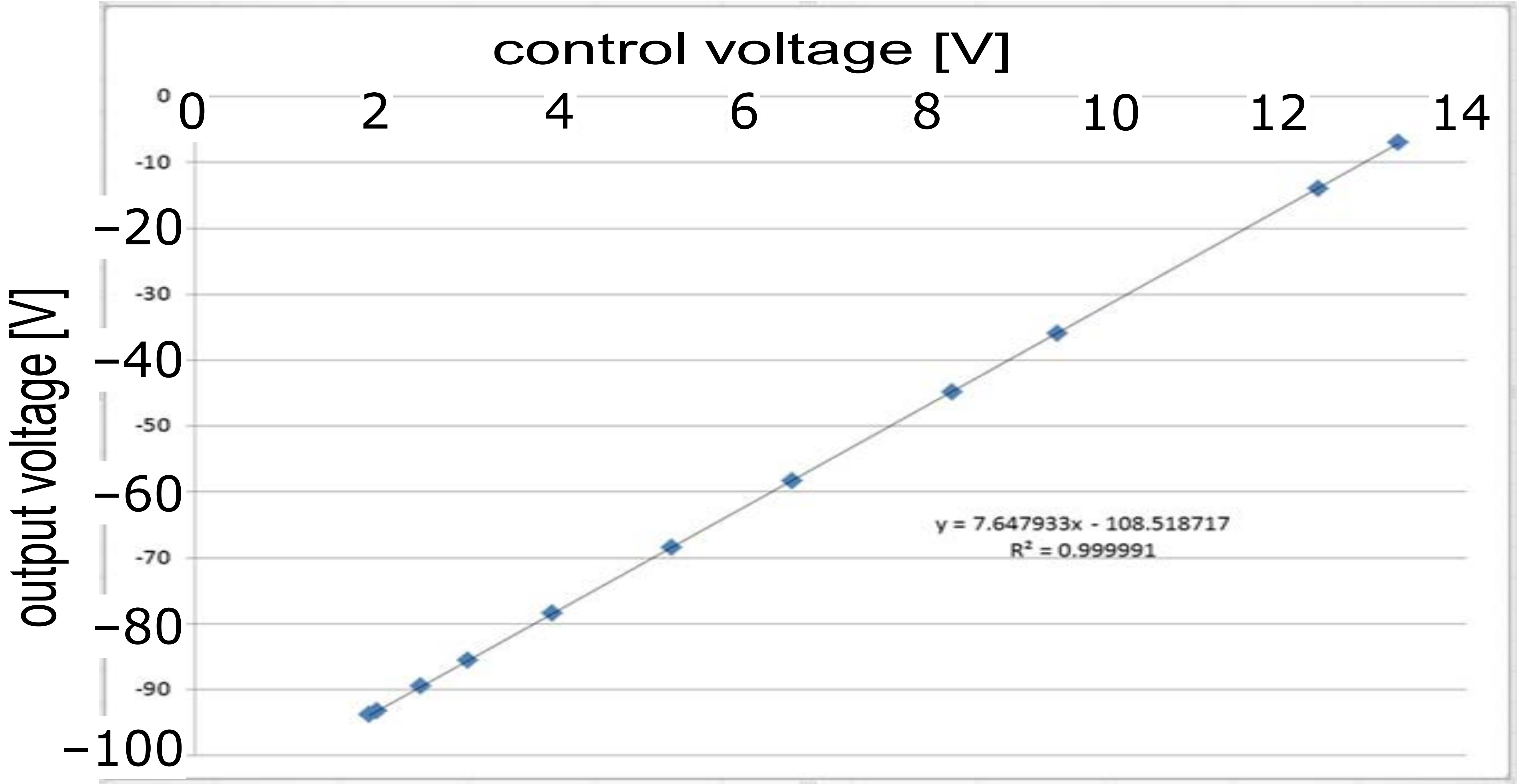
- Ringing (150-200 MHz) at edges of capacitor reload signal
- Worse at low temperatures
- Cannot filter without significant distortion of real photon signal

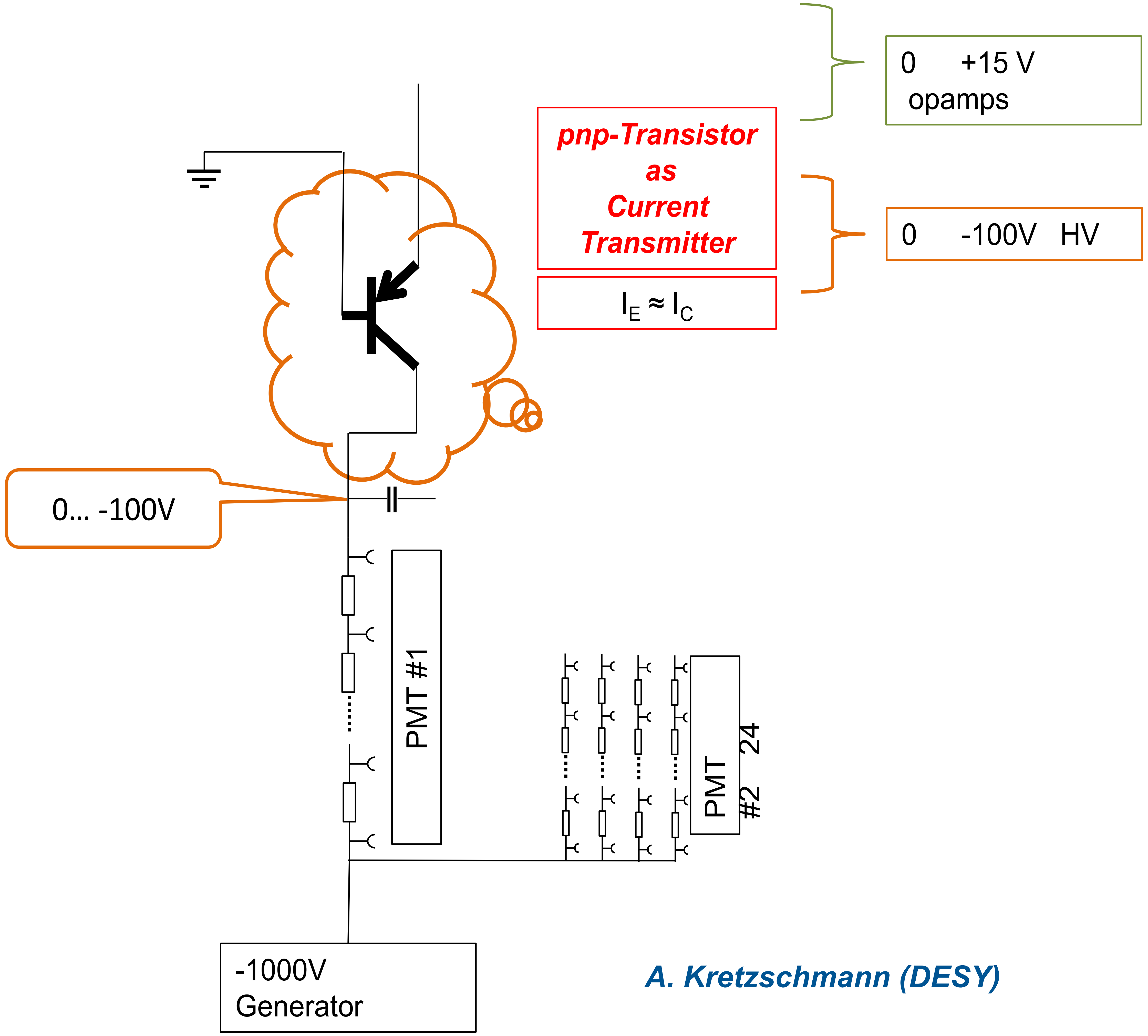




HV generation — alternative design

- Central generation on mainboard
- Adjustable and switchable for each PMT individually
- Resistive voltage divider on PMT base
- Prototype power consumption: 1140 mW per module, plan to reduce to 740 mW / module





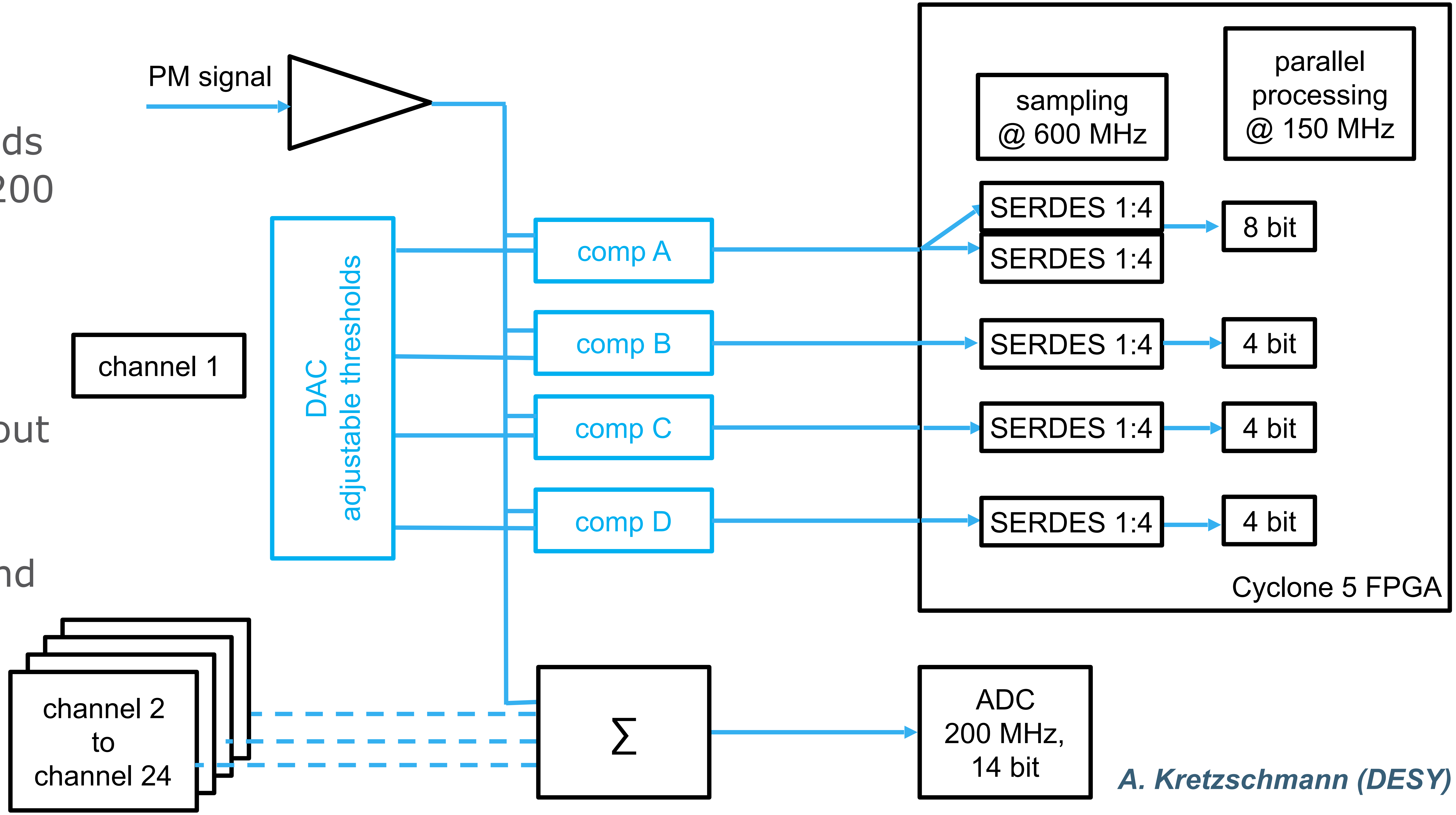
A. Kretzschmann (DESY)

Front-end — 4-comparator (ToT) readout

Features

- 24 channels
- 4 programmable thresholds per PMT, sampled with 1200 (600) MS/s
- analog sum of all PMT signals sampled with 200 MS/s ADC
- no deadtime during readout
- double pulse resolution around 10..12 ns
- power consumption around 5 W per mDOM

Tradeoff between power and bandwidth



A. Kretzschmann (DESY)

Front-end — ToT readout with multi-comparator ASIC

Provides large number of comparators while remaining low in power consumption

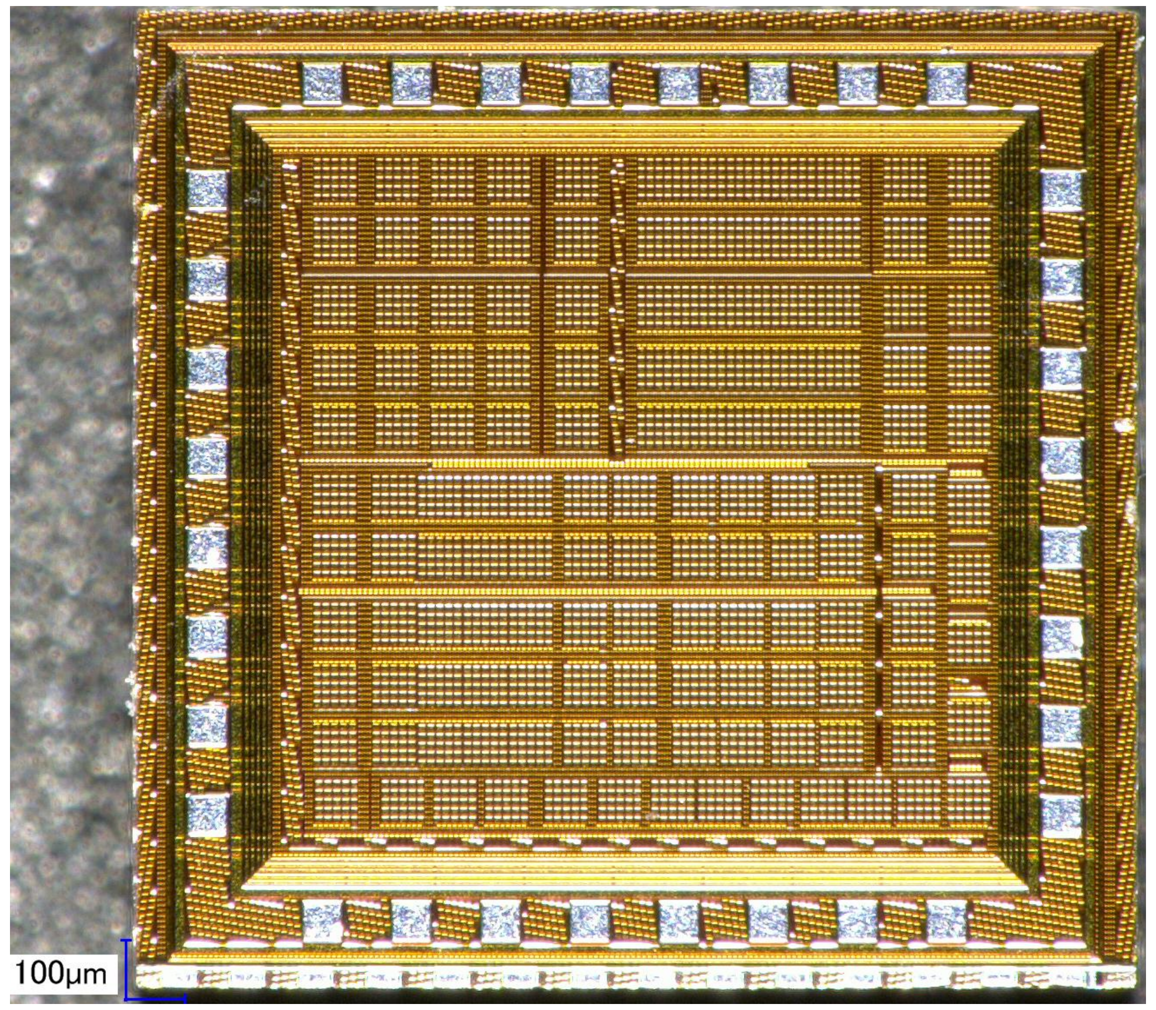
High-level ASIC specification

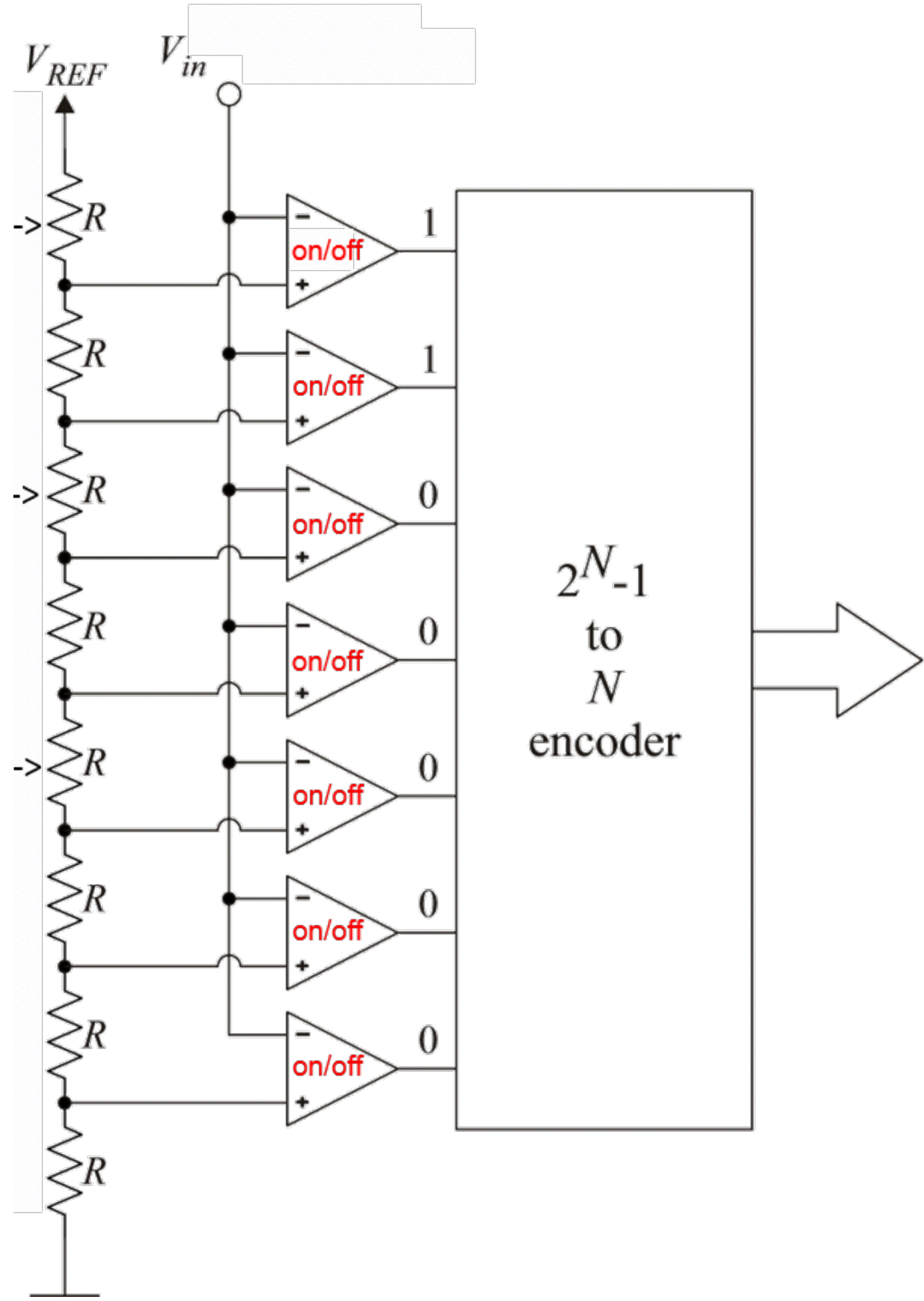
- 8 bit (256) equally spaced reference resistor chain → dynamic range ~64 pe if lowest level at 0.25 pe
- 6 bit (63) comparators (can be freely assigned to resistor levels prior to production)
- Internal reference frequency up to 500 MHz
- Power consumption < 40 mW

Status

- First prototypes available (5 bit comparators + 6 bit resistor chain)
- Currently under testing

picture first of prototype



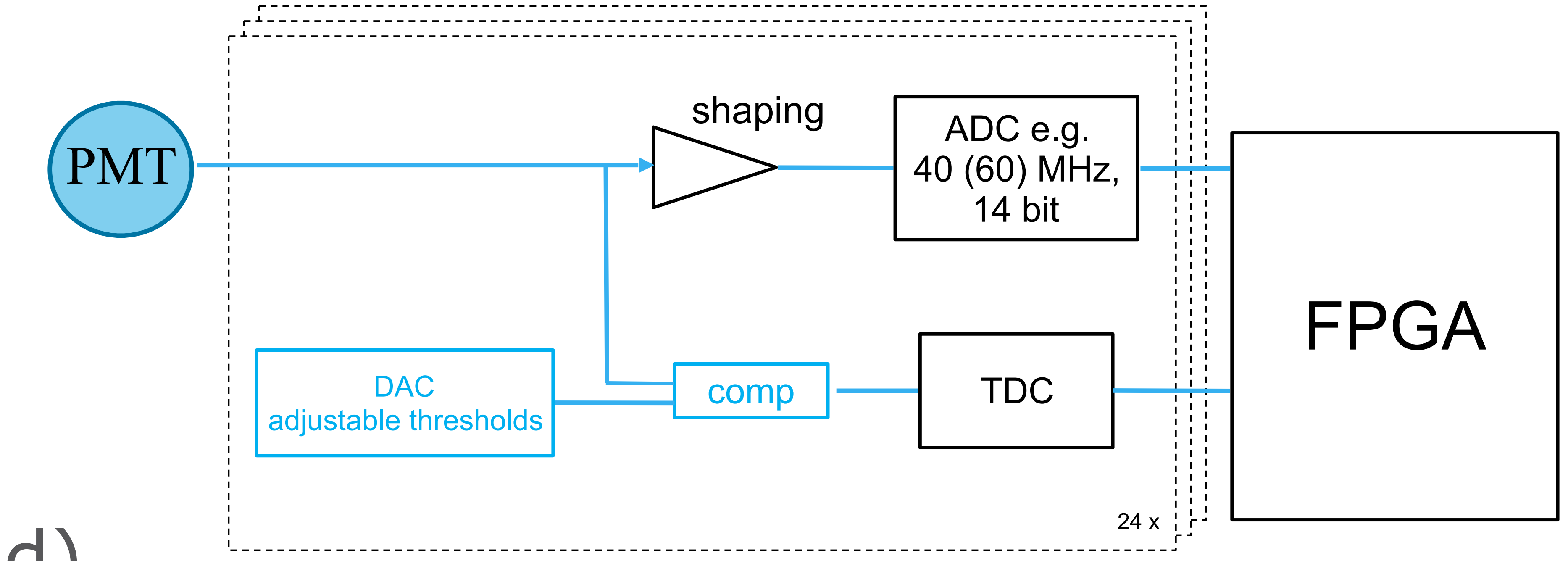


Alternative readout designs under investigation

ToT readout (in particular 4-ToT version) might not deliver sufficient resolution for double pulses and/or complex waveforms (depends also on bandwidth of pre-amplifier and power constraints)

Slow ADC combined with precise leading edge time

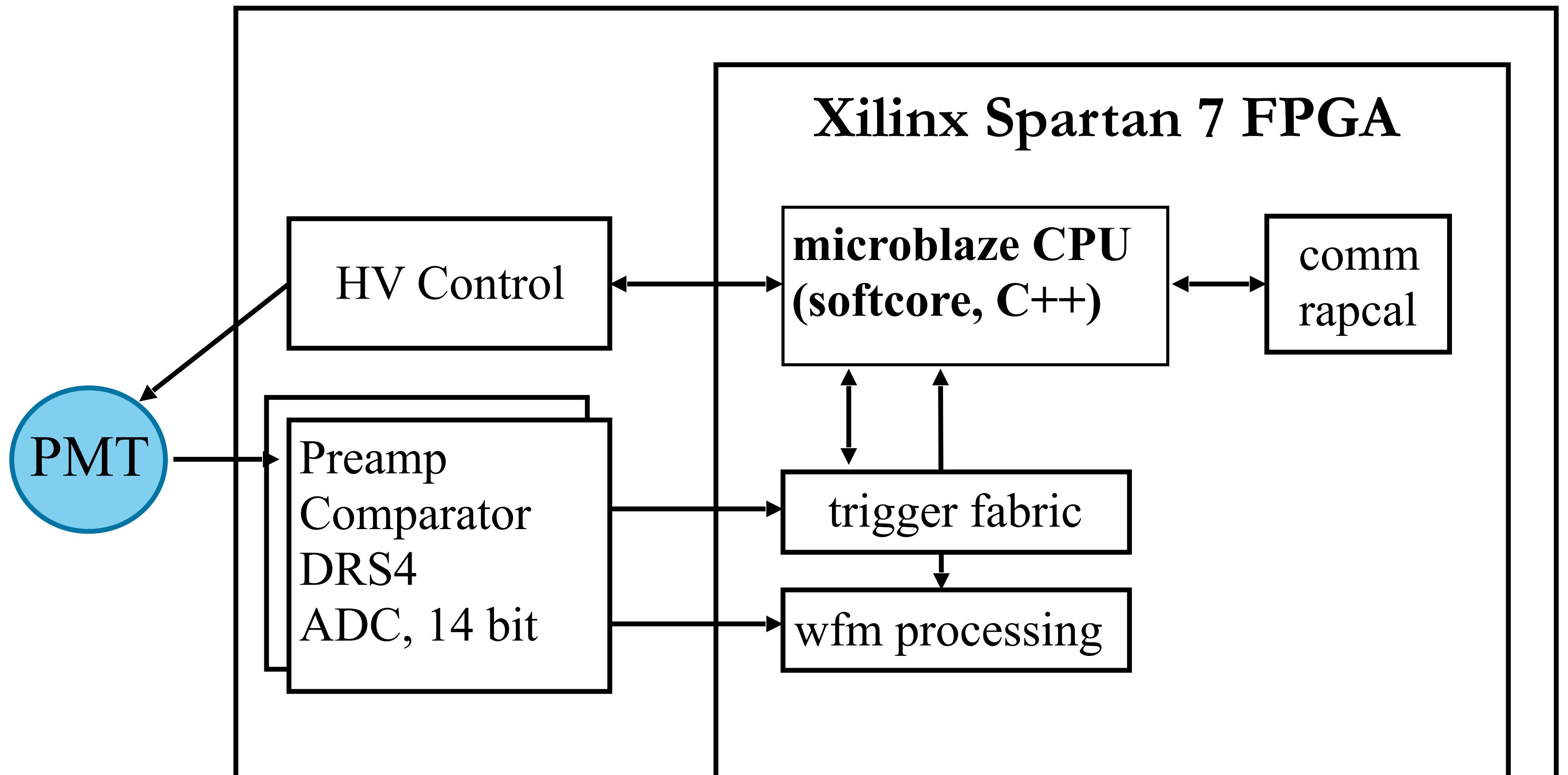
- Pro
  - individual waveforms for each PMT
  - good charge and leading edge resolution
- Con
  - limited double pulse resolution (depends on ADC sampling speed)



P. Sandstrom, B. Ty, Ch. Wendt (UW Madison)

Fast waveform sampling with DRS4

- Pro
  - High-resolution waveforms
  - Reasonable power consumption
  - Full waveforms for each PMT
- Con
  - Deadtime
  - Groups of eight PMTs tied to simultaneous readout



K. Sulanke (DESY)

Summary and outlook

- A multi-PMT optical module is being developed for deployment in the deep ice at the South Pole for future IceCube extensions
- Harsh environmental conditions and available infrastructure pose stringent limits on module parameters like size, power consumption and reliability
- Mechanical design well advanced → optimizations towards final design
- Several options for readout under evaluation → find best compromise between power consumption and precision of PMT waveform sampling in view of physics case

Rough timeline

- end of 2018: demonstrator
- end of 2019: final design
- 2020—2021: production
- 2022/23: deployment

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