Photosensor studies

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Overview

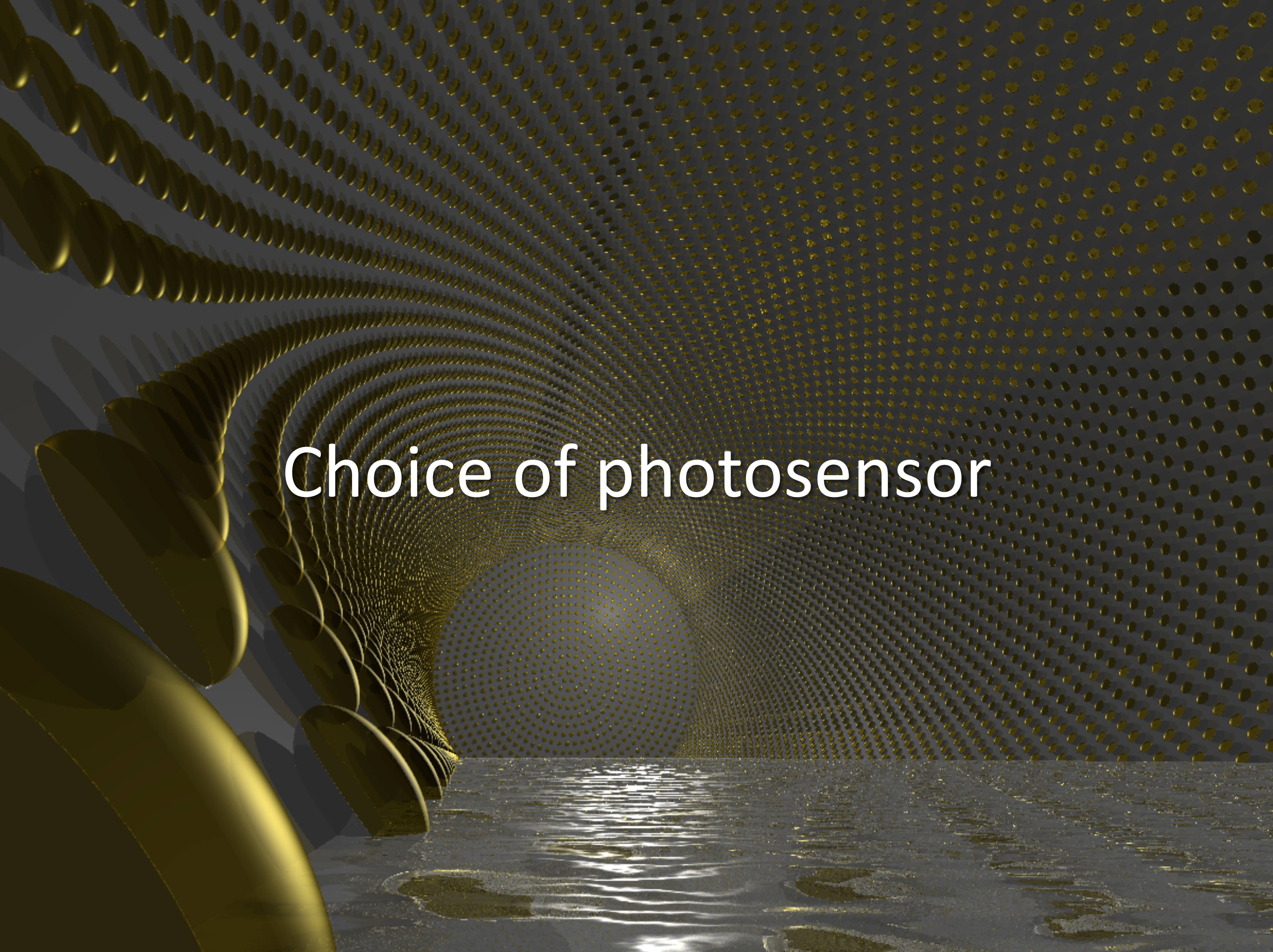
Choice of photosensor

- Crucial properties
- Influence of sensor properties on detector behavior
- Photosensor testing facility in Munich
- SiPMs: dark count
- Alternative photosensor types

Optical Module for PMTs

- Design
- Pressure withstanding encapsulations
- Light concentrators: effective area increase

Summary + possible topics for discussion



Choice of photosensor

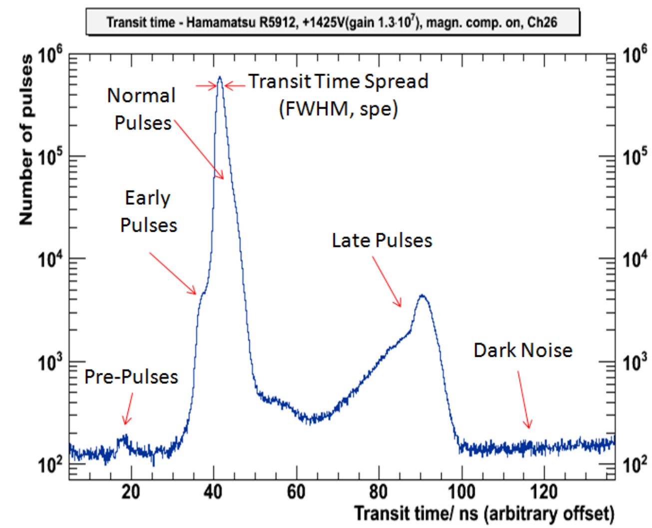
Crucial photosensor properties

Property	Requirement
Timing uncertainty (single photoelectrons(spe), FWHM)	<3.0ns
Early pulses	<1%
Late pulses	<4%
Quantum efficiency @420nm	>21%
Optical coverage, using 1.75x light concentrators	30%
Dynamic range	spe→0.3pe/cm²
Gain (PMTs)	$>3 \cdot 10^6$
Peak-to-valley ratio (spe)	>2
Dark count	< 15Hz/cm²
Slow afterpulses (0.2-200µs)	<5%
Fast afterpulses (0-200ns)	<5%
Pressure resistance	>13bar
^{238}U content	$< 3 \cdot 10^{-8}$g/g
^{232}Th content	$< 1 \cdot 10^{-8}$g/g
^{nat}K content	$< 2 \cdot 10^{-5}$g/g
Lifetime	>30y

probably needs to be increased

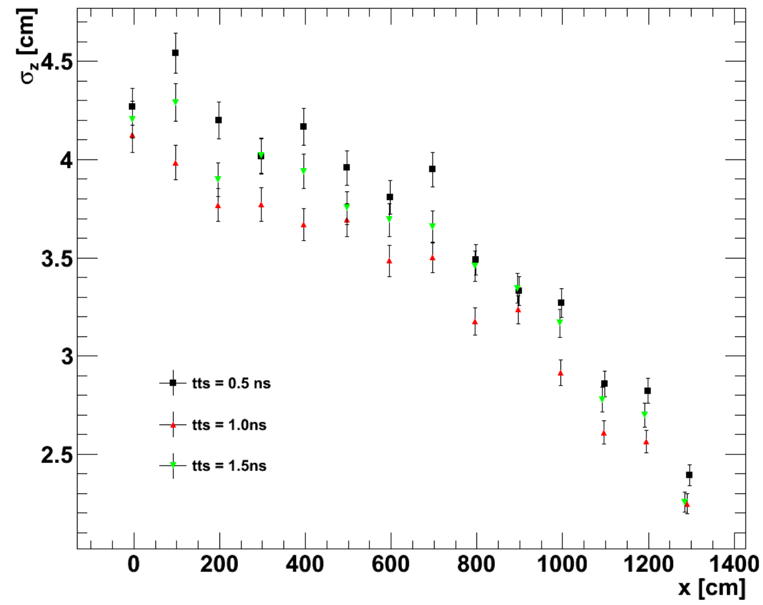
update possible?

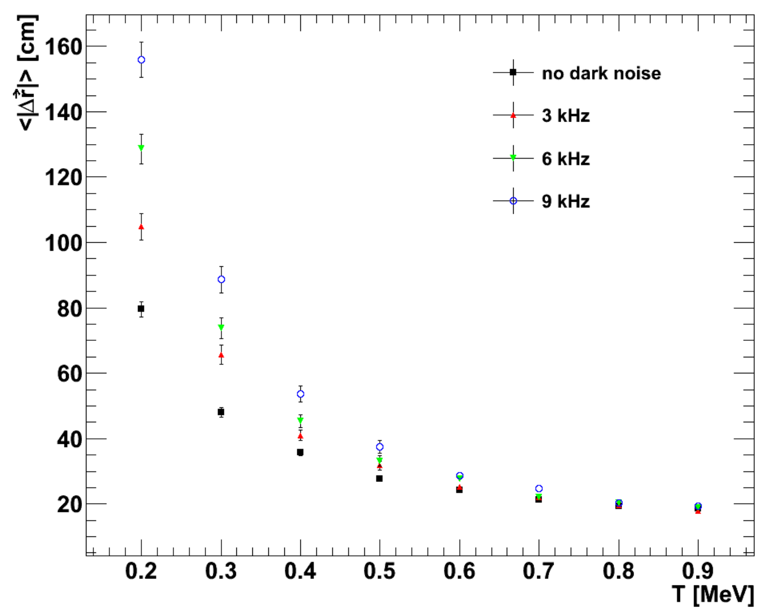
PXE still an option? smaller tank with larger radius?



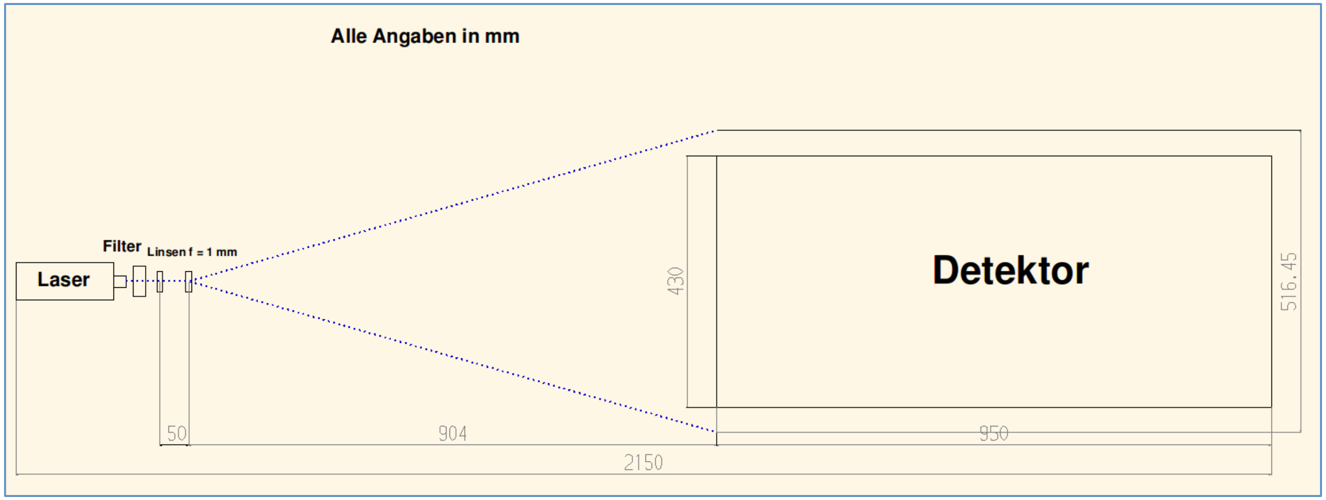
Influence of sensor properties on detector behavior

- Determine influence through Geant4 based Monte Carlo simulations
- Position and energy resolution (Dominikus Hellgartner)
  - Timing uncertainty:
    - First simulations, still fighting some problems with small timing uncertainties
    - First impression: no big influence
  - Dark Noise:
    - No big influence for energies around 1MeV or bigger
    - For 200keV position + energy resolution ≈30% worse
- α/β-discrimination (Randolph Möllenberg)
  - Dark Noise:
    - Strong influence on efficiency
  - Late Pulses + Fast Afterpulses
    - Negligible effect
  - Winston Cones (50°opening angle)
    - Improve separation by factor two





Munich photosensor testing facility



Michael Nöbauer

- Laser: Edinburgh Instruments EPL-405-mod, ps pulsed diode laser, 403nm, repetition rates 2kHz-2MHz, 48ps FWHM (@2kHz), ≈11µW average power (@2MHz)
- Neutral density filters: Variable attenuation
- Optics: 2 focussing lenses with extremely small focal lengths (≈ 1mm)
  → Expand beam radius from 100µm (w_0) to ≈ 10m within 90cm, approximately Gaussian beam profile at center
  → Good homogenity of beam intensity from r=0cm to r=20cm
  However: incident angle ≈14° @r=20cm due to small length of dark box
- Apertures: Between + after lenses, each with two layers of black felt attached, stretching to walls, to eliminate stray light
- Photosensor: Up to 15“ diameter / 12“ with light concentrator with 2× area increase
  - PMT holder: PMT can be moved horizontally + vertically and rotated
- FADC: Acqiris DC282, 2Ch with 4GHz sampling, 10bit

Was set up in a Diploma thesis by ***Michael Nöbauer***

Munich photosensor testing facility

Michael Nöbauer

So far:

- Eliminate stray light:
  - Covered last aperture, 8" PMT + scaler
    → No time correlated coincidences
- Intensity variations:
  - Contribution from Gaussian beam profile, smaller for high maximum incident angle
  - Contribution from obliquely incident light at maximum angle, bigger for high max. inc. angle
  - Sum minimal for $\Delta I_{Gauss} \approx 0.1\%$ and $\Delta I_{oblique} \approx 3\%$

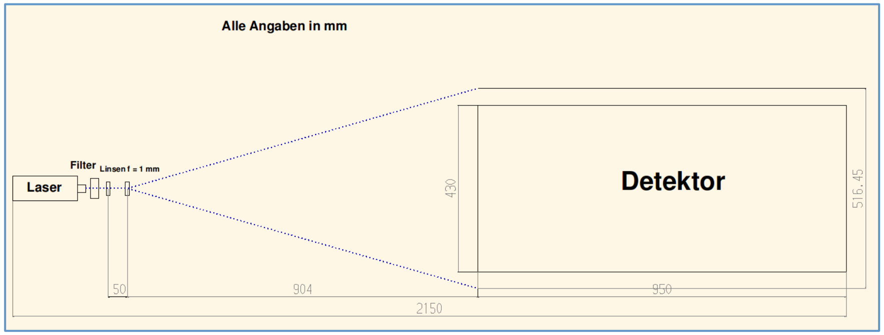
  - Test homogenity with different lenses and varying focal lengths: ball lenses + GRIN lenses
    - Status: Have adjusted optics with 2 ball lenses (f=1.1mm), 35mm distance
      → Currently measuring homogenity with 1" PMT

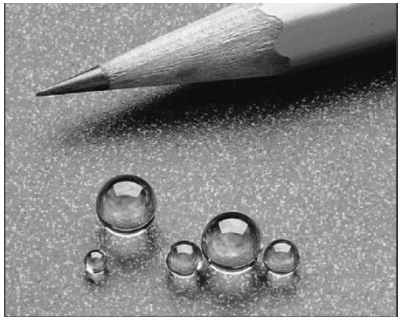
To do:

- Finish analysis software
- Improve FADC readout speed
  → *Will be treated in a Bachelor thesis by Christina Frost*
- Long term: include fiber optics
  → Laser in separate dark box, direct surface scan

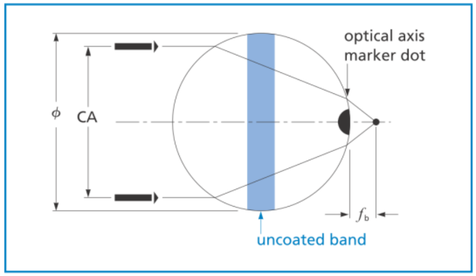
Goals:

- Measure large area photosensors (with light concentrators), e.g. PMTs
  - With optics: complete area at the same time, for different incident angles
  - Without optics: can scan surface with varying incident angles

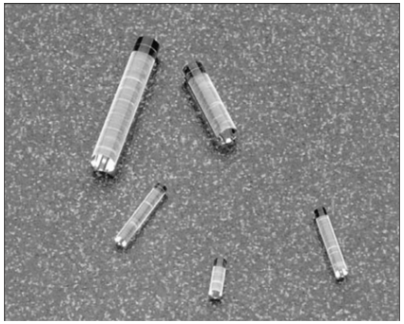




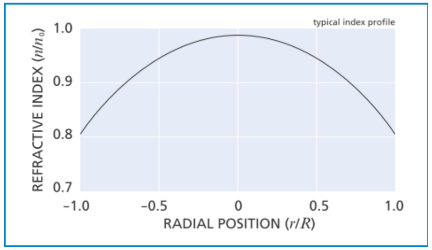
Ball lenses

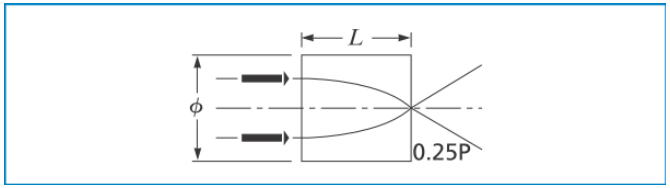


Spherical ball lens



Gradient Index (GRIN) lenses





CVI Melles Griot

SiPMs: Dark count

- Estimation of artificial events through dark noise (very optimistic)
  - Dark noise: 100kHz/mm² @300K
  - Peltier cooler → 230K (-40°C) → goes down by ≈factor 300 (paper by Jozsef Janicsko) → 300Hz/mm²
  - 30% optical coverage, concentrators (area ×2) → ≈1500m² active surface (1 detector, 50kt)
  - Assume photo detection efficiency = 65% → 3× better than PMTs → need only 500m² for comparable photo electron yield
  - Overall dark noise rate = $500 \cdot 10^6$ mm² · 300 Hz/mm² = $1.5 \cdot 10^{11}$ Hz
  - Time window needed to look for low energy events:
    - Assumptions: want to be able to see all events in FV, no slow decay component, only sensors at same z as event detect photons → time window =mere transit time through FV

$$\Delta t = \frac{s}{v} = \frac{d_{FV}}{\frac{c}{n}} = \frac{2 \cdot 11\mathrm{m}}{\frac{0.3\,\mathrm{m/ns}}{1.5}} = 110\mathrm{ns} \approx 100\mathrm{ns}$$

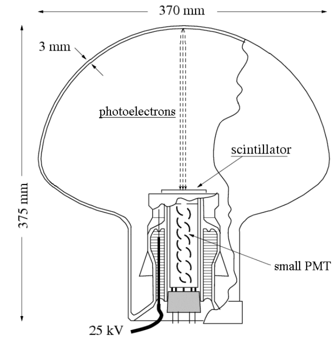
  - Average coincidence rate in time window of trigger = 100ns · $1.5 \cdot 10^{11}$ Hz = 15000 dark noise pulses
  - Light yield ≈ 200p.e./MeV
  - Energy threshold set by dark noise = 15000 pulses/ 200 pulses/MeV = **75MeV**
  - *Very rough estimate !*
  - However: With a trigger configuration like this LENA couldn't be used for low energy physics

→ Reanalyze threshold imposed by SiPM dark count with more appropriate, particle physics like local triggers + reconstruction methods

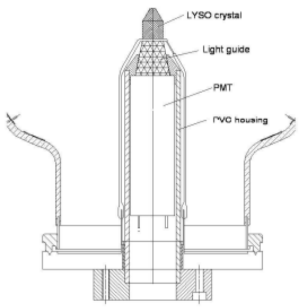
- Worst case: dark count still too high for low E physics or α/β discrimination
  - Maybe as complimentary sensor for higher energies
  - Maybe in form of hybrid detector

Alternative photosensor types

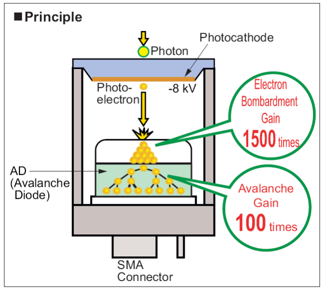
- Crucial question: Available in high quantities in time for construction?
- Possibly available for first detector:
  - QUASAR (14.6“):
    - Layout: Photocathode → HV → scintillator crystal → small PMT;
    - Very promising sensor in most regards (tts, DN, AP, …), are even working to further improve design with faster scintillator + fast small HQE PMT;
    - Drawbacks: currently no manufacturer, dynamic range=?
  - X-HPD (8“):
    - Layout: basically as QUASAR
    - Drawbacks: high dark rate, 100-10Hz/cm², dyn. range=?
  - HAPD (13“):
    - Layout: Photocathode → HV → APD
    - Expect commercial availability in spring 2012 (status Jan. 2011)
    - Drawbacks: dyn. range?
  - QUPID (3“):
    - Layout: same as HAPD
    - Drawbacks: small size, designed for LAr/LXe, dark count @RT =?, QE=?, dyn. range?
- Need to test samples to determine all properties



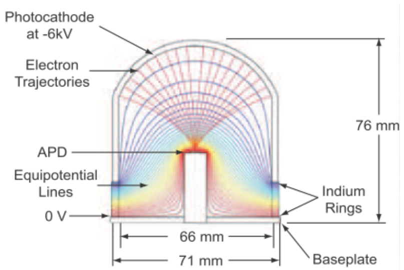
QUASAR-370



X-HPD



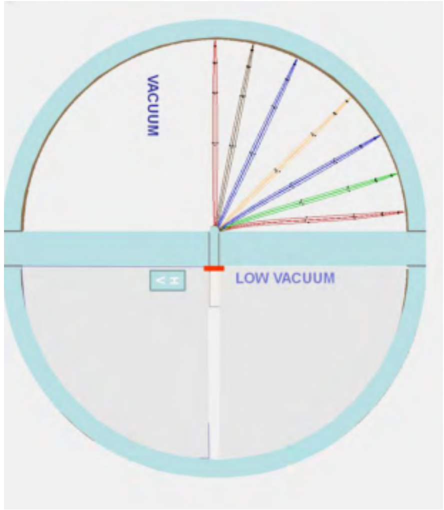
HAPD



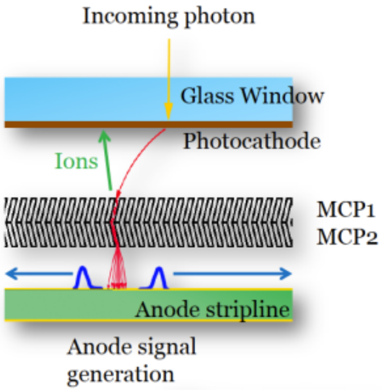
QUPID

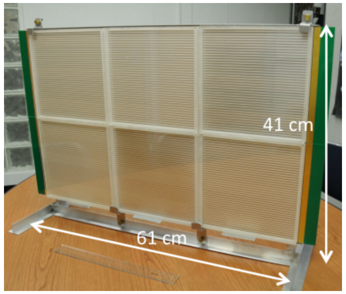
Alternative photosensor types

- Probably not available in time:
  - Abalone (≈13“):
    - Layout: Photocathode → HV → scintillator crystal → G-APD
    - Advantages: simple, robust + cheap design
    - Status: Prototypes not yet stable under atmospheric pressure
  - LAPPD (scalable):
    - Layout: Photocathode → 2 microchannel plates → anode striplines read out at both ends
    - Advantages: ps time resolution, large area, position sensitive, cheap(?)
    - Status: working prototypes of MCP sheets + electronics, QE still low, no complete prototype yet



Abalone

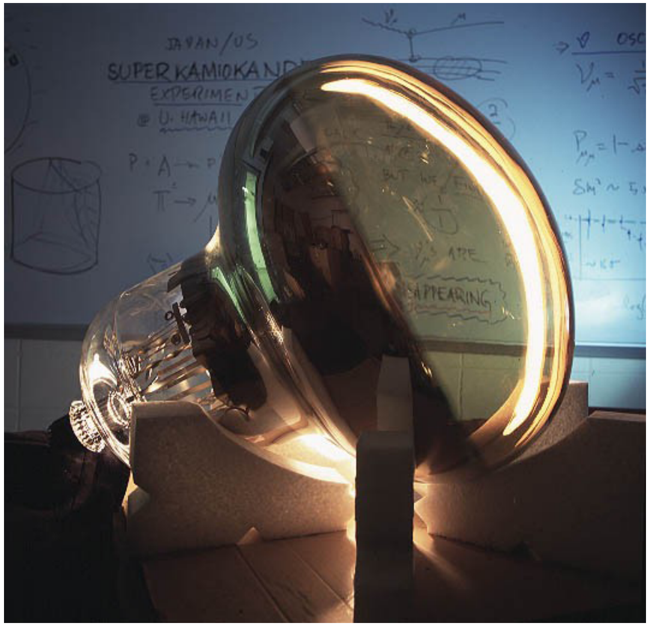




LAPPD

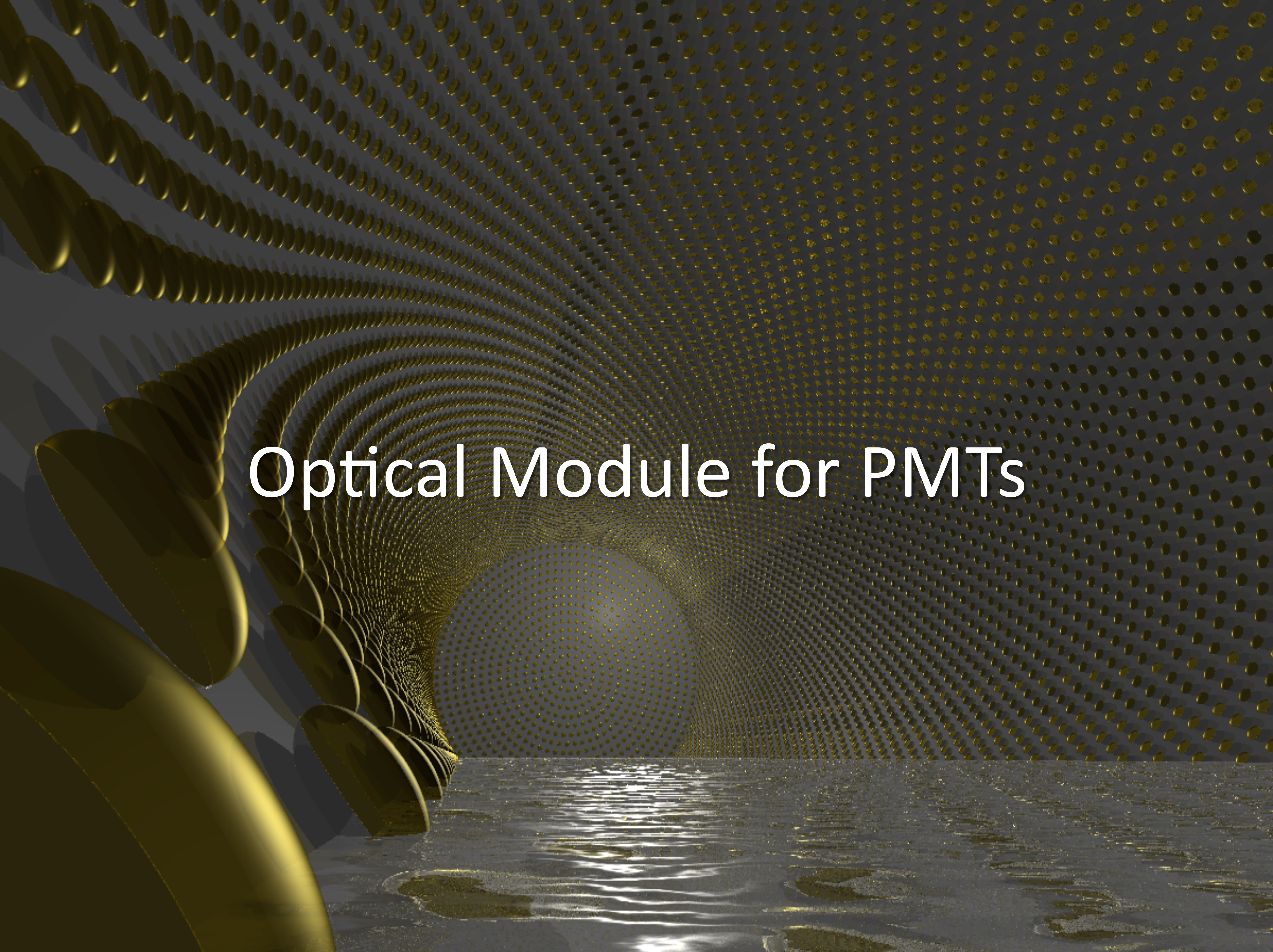
Choice of photosensor: status

- At the moment PMTs favoured option: so far only photosensor which is likely to fulfill all criteria
- Promising alternatives: determine properties
- Keep an eye on new developments



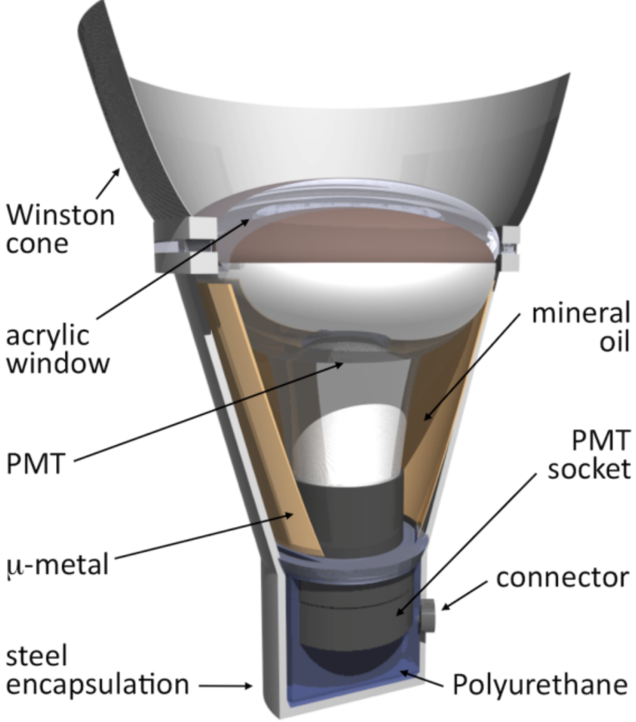
Until when do we have to decide on the photosensor type?

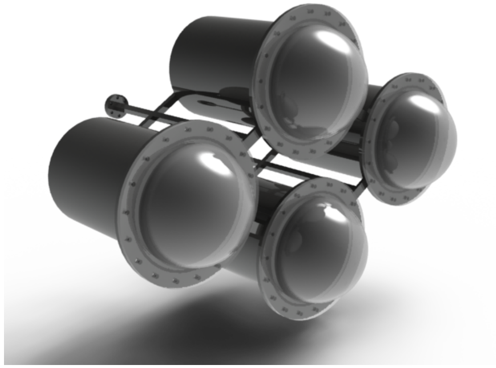
Optical Module for PMTs



PMT optical module: Layout

- PMT + voltage divider
  - Determine requirements → in progress
  - Measure properties → in progress
    - Selection of best series → to do
    - Modifications? → to do
- Mu metal
- Pressure encapsulation
  - Design (include design of OM) → in progress
    - Simulations → in progress
      - Build prototype → to do
        - Test: pressure tank, radiopurity, long term → to do
- Light concentrator
  - Simulations → in progress
    - Build prototype → to do
      - Test:
        - Optical properties → to do
        - Material compatibility → in progress
- Connections to other PMTs (arrays) + rack/wall

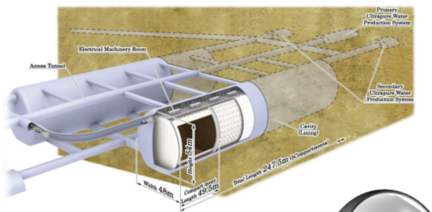


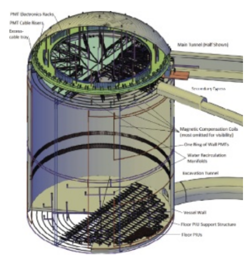


Pressure withstanding PMT encapsulations for LENA: Why encapsulate PMTs?

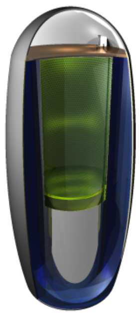
HyperK

Hyper-Kamiokande detector





LBNE



LENA

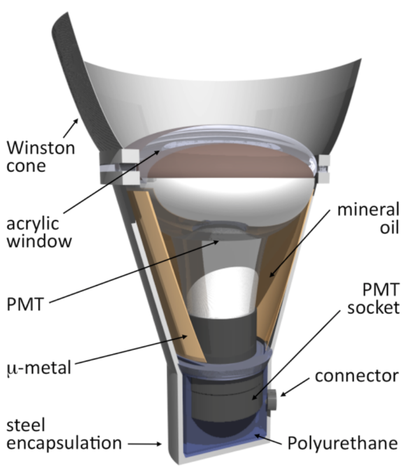
- Next-generation land-based neutrino experiments like HyperK, LBNE or LENA use tanks with heights of 50-100m

  → High pressure at the tank bottom

  - LENA: ≈9.8bar(LAB) + safety margin

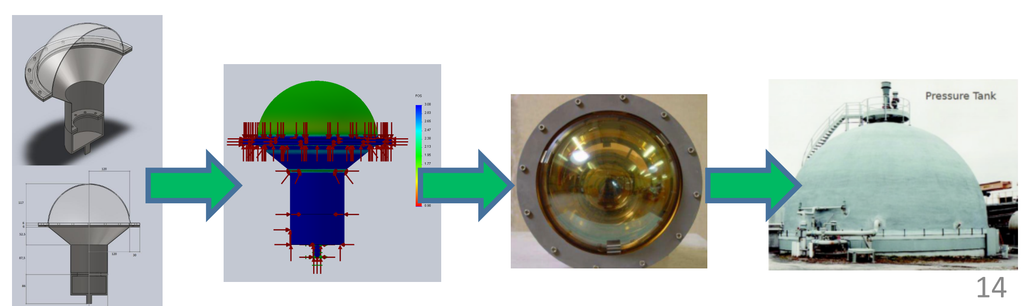
  → At the moment no available PMT model fulfills requirements

- a) Develop new PMTs (LBNE)
- **b) House PMTs in encapsulations (LENA)**
  - ✚ No restrictions on PMT model to be used
  - ✚ Cheaper?
  - ✚ Faster development
  - ✚ LENA: certainly possible to fulfill requirements
  - ▬ Introduce radioactivity



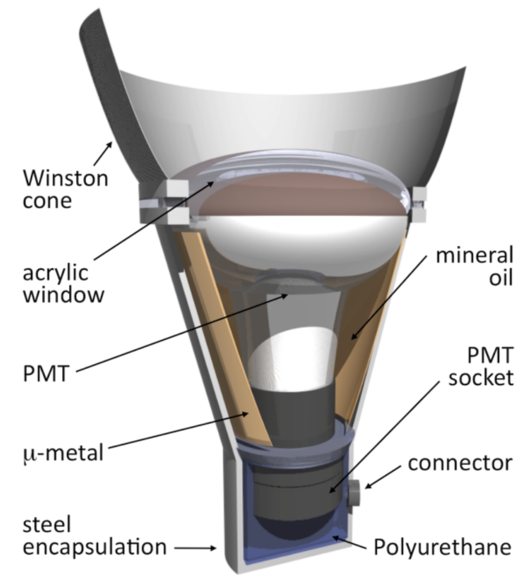
How to develop an encapsulation?

- *Design, pressure simulations*, build prototype, pressure tests



Pressure withstanding PMT encapsulations for LENA: Design

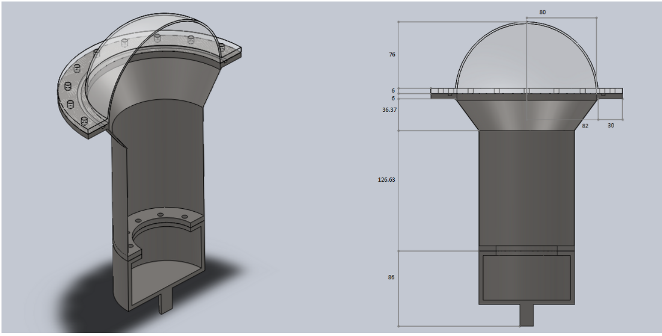
- Configuration
  - Acrylic glass transparent window
  - Stainless steel body housing, one or two parts
  - Also incorporate Mu-metal, Winston Cone and connection to other PMTs + tank
    - *Not crucial for pressure simulations → at a later date*

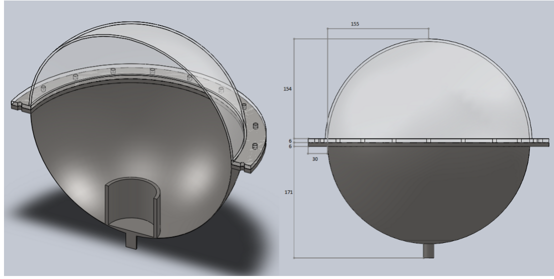


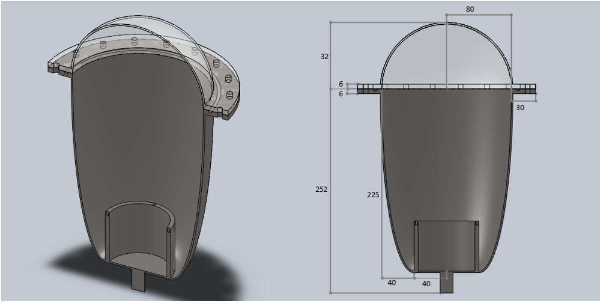
- Different encapsulation designs
  - Conical
    - Based on Borexino + Double Chooz encapsulation
  - Spherical
    - As in deep sea neutrino telescopes / IceCube
  - Elliptical
  - Cylindrical

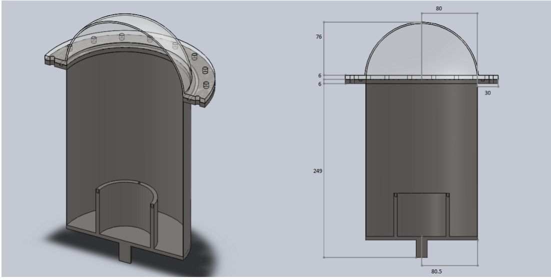
- Create engineering drawings with CAD software:
  - SolidWorks Educational Edition Academic Year 2010-2011 SP4.0

Pressure withstanding PMT encapsulations for LENA: Design









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Pressure withstanding PMT encapsulations for LENA:
Pressure simulations

- Simulate behaviour under pressure with a Finite Elements Analysis (FEA) simulation software
  - Engineering drawings and FEA pressure simulations were done with same software
- Software: SolidWorks Educational Edition Academic Year 2010-2011 SP4.0, *Simulation Premium package*
- Settings: Linear static study, 12bar pressure, node distance 3mm ± 0.15mm
- Materials: High impact resistant acrylic glass, 1,4404 stainless steel X2CrNiMo17-12-2
- Computer: Intel i7-2600, 8GB DDR3-RAM, AMD Radeon HD 6450 1GB GDDR3, Win7 Prof. 64bit
- So far designs + simulations for 5 candidate PMTs:
  - Hamamatsu: R7081 (10“), R5912 (8“), R6594 (5“)
  - Electron Tubes Enterprises Ltd.: 9354 (8“), 9823 (5“)

German Beischler

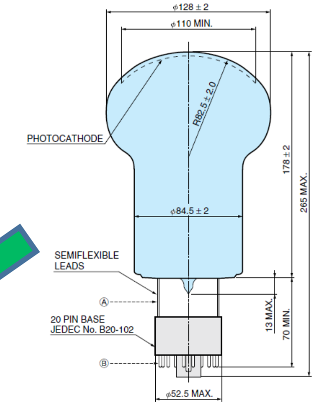
- *Was treated in a bachelor thesis by* ***German Beischler***
  - *In consultance with Harald Hess (head of workshop + SolidWorks expert of our chair)*
  - *Continues these studies!*

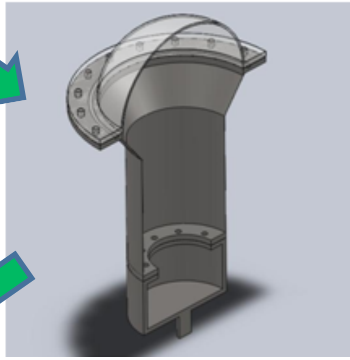
Pressure withstanding PMT encapsulations for LENA:

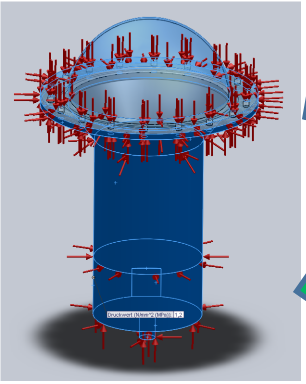
Pressure simulations

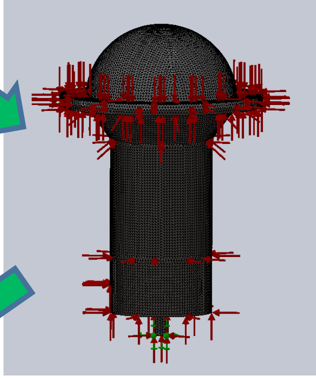
Procedure:

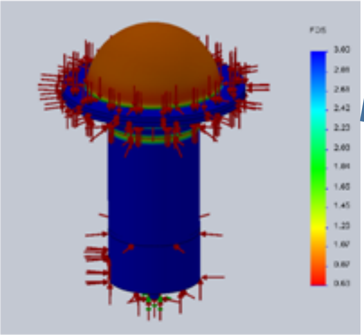
- Import PMT contour from engineering drawing in datasheet
- Rotate to obtain model of PMT
- Construct encapsulation based on PMT dimensions and experience from design of the Borexino + Double Chooz encapsulation
- Simulate encapsulation with 12bar pressure applied
  - Apply forces → meshing → simulate to determine factor of safety
  - Vary thicknesses of acrylic glass + stainless steel to find minimum values
- Compare results for different designs regarding weight (U, Th, K impurities in materials), surface (adsorbed Rn) and construction costs





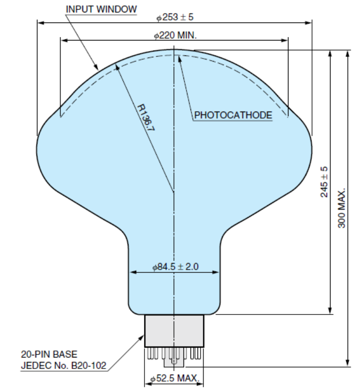


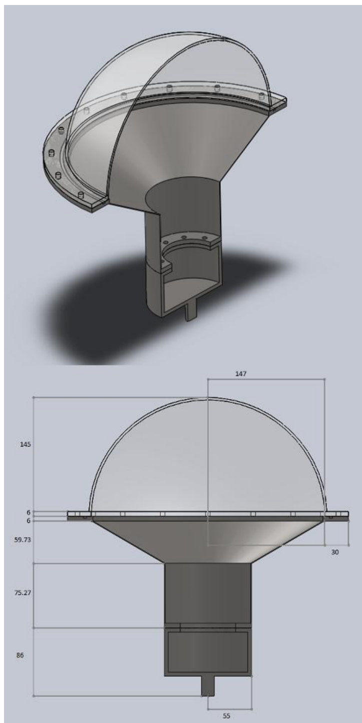


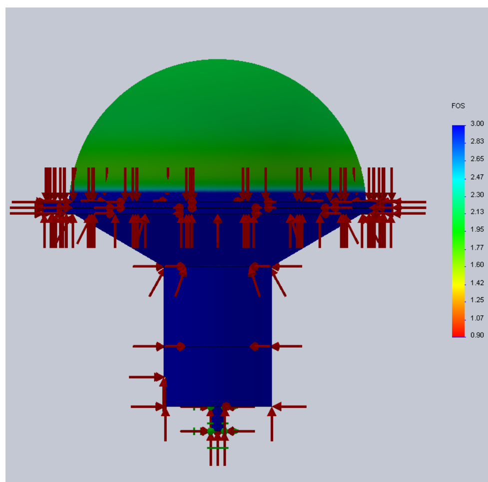


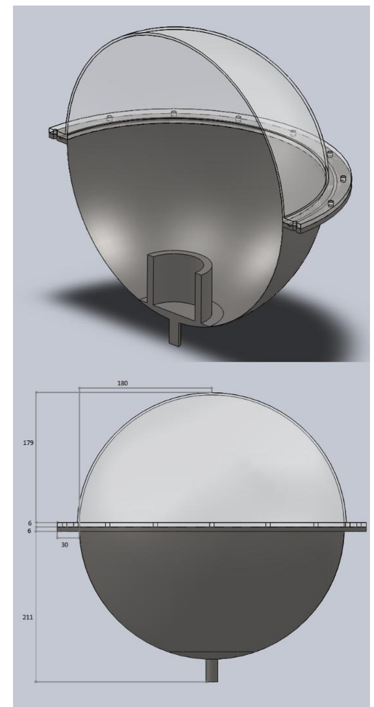
Pressure simulation results:

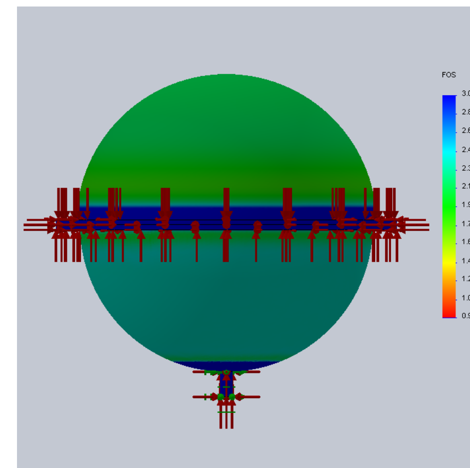
Hamamatsu R7081 (10")











<u>Conical encapsulation:</u>

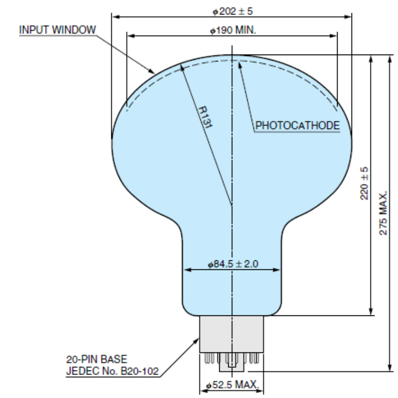
Steel:	2mm thickness,	4.38kg
Acrylic glass:	4mm thickness,	0.86kg
Total surface:	0.69m²	

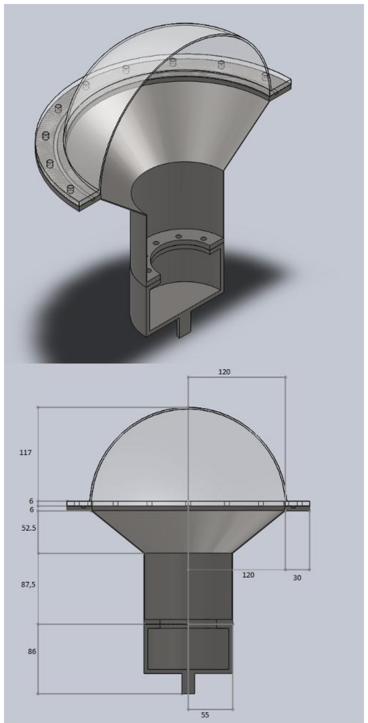
<u>Spherical encapsulation:</u>

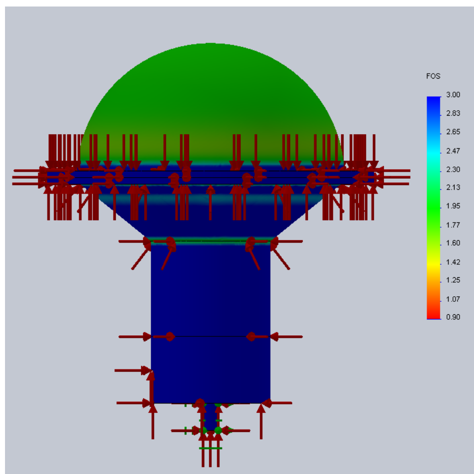
Steel:	0.5mm thickness,	4.08kg
Acrylic glass:	5mm thickness,	1.48kg
Total surface:	1.01m²	

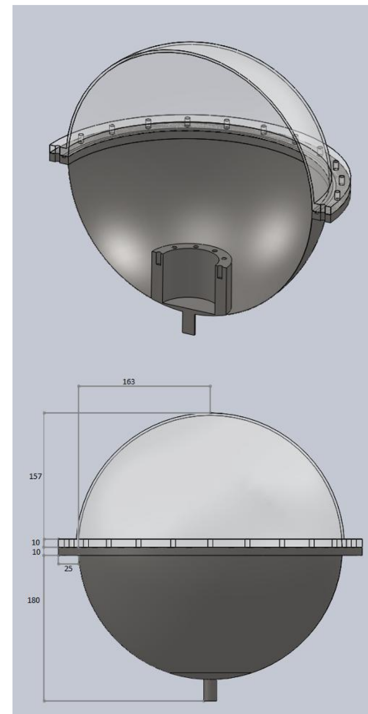
Pressure simulation results:

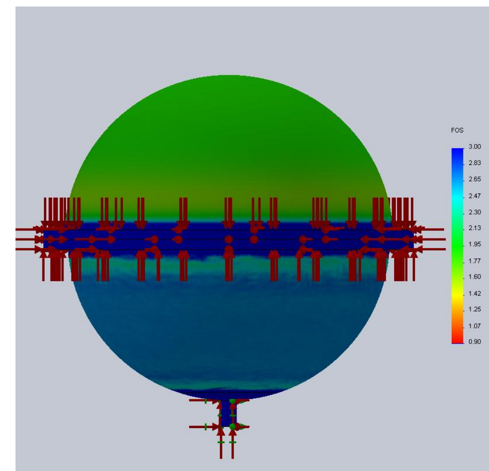
Hamamatsu R5912 (8“)











<u>Conical encapsulation:</u>

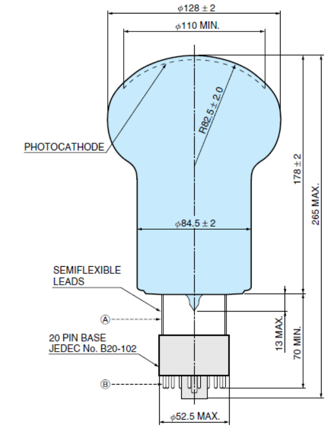
Steel:	1mm thickness,	3.24kg
Acrylic glass:	3mm thickness,	0.50kg
Total surface:	$0.53m^2$	

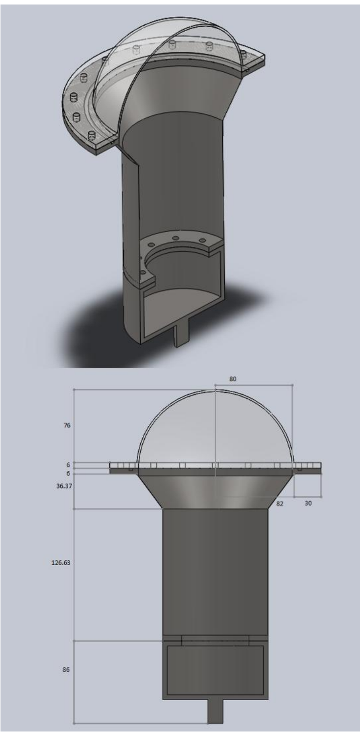
<u>Spherical encapsulation:</u>

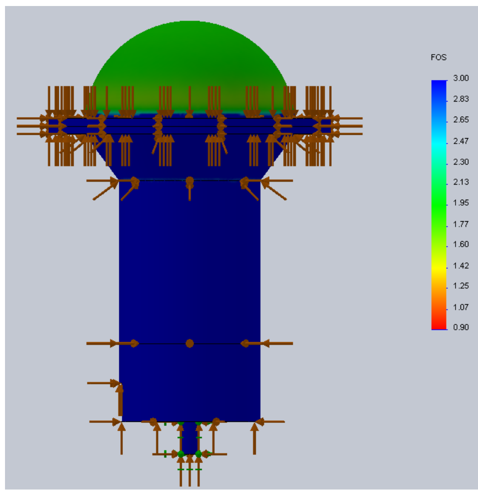
Steel:	0.5mm thickness,	4.66kg
Acrylic glass:	4mm thickness,	1.10kg
Total surface:	$0.83m^2$	

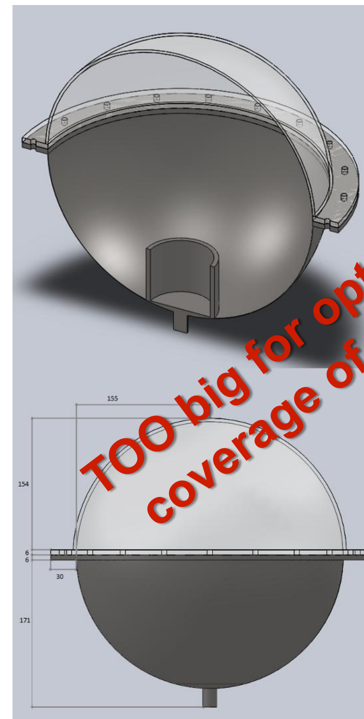
Pressure simulation results:

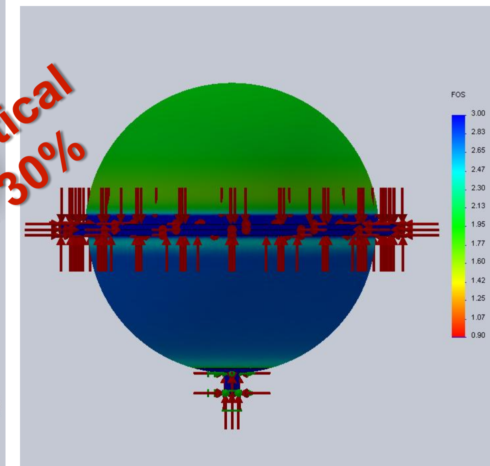
Hamamatsu R6594 (5“)











TOO big for optical coverage of 30%

Conical encapsulation:

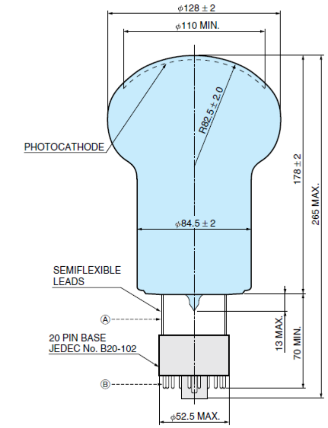
Steel:	1mm thickness,	2.77kg
Acrylic glass:	2mm thickness,	0.22kg
Total surface:	0.37m²	

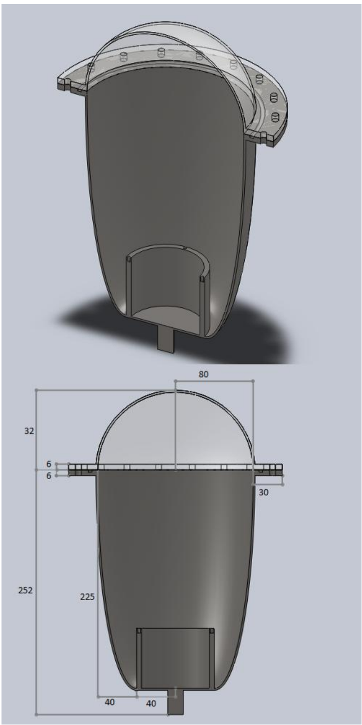
Spherical encapsulation:

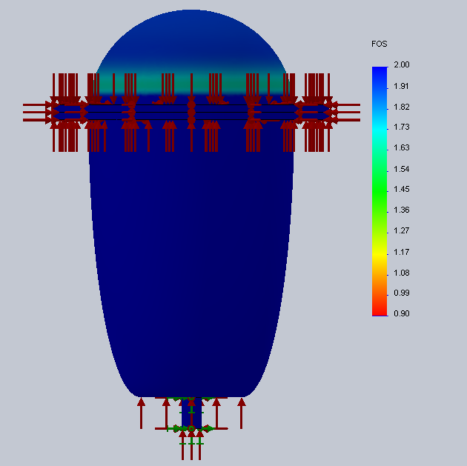
Steel:	0.5mm thickness,	2.75kg
Acrylic glass:	4mm thickness,	0.94kg
Total surface:	0.78m²	

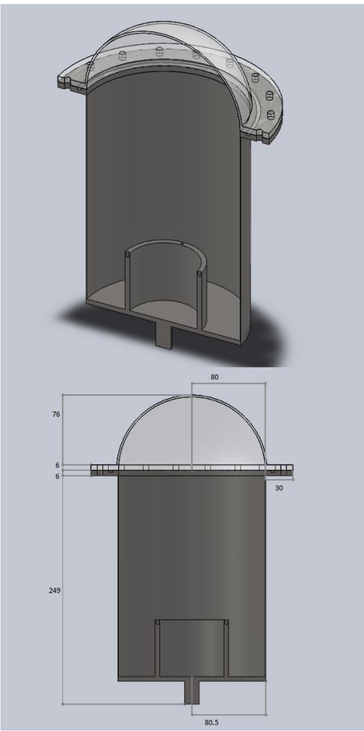
Pressure simulation results:

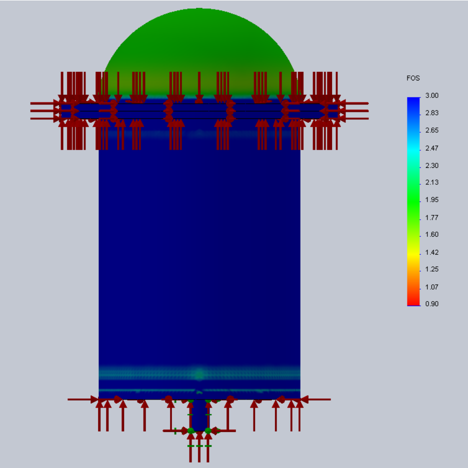
Hamamatsu R6594 (5")





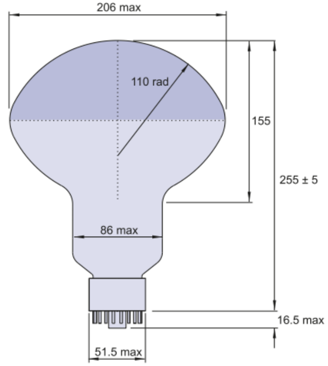






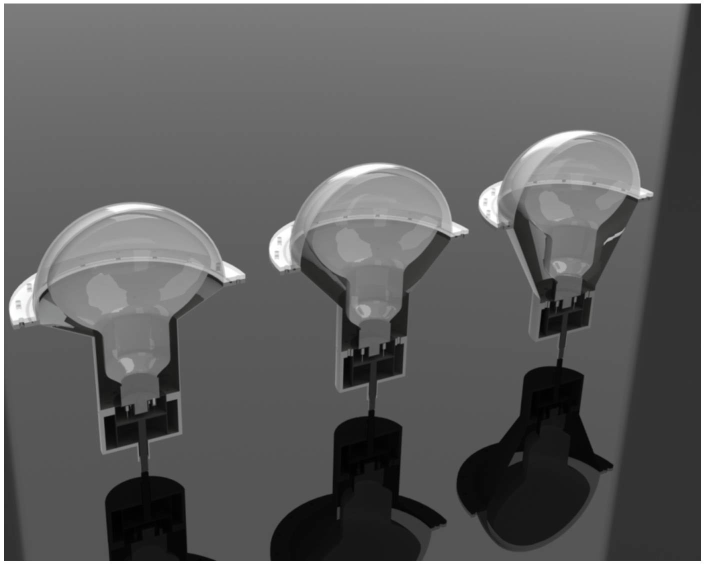
<u>Elliptical encapsulation:</u>
Steel: 2mm thickness, 3.06kg
Acrylic glass: 2mm thickness, 0.22kg
Total surface: $0.41 m^2$

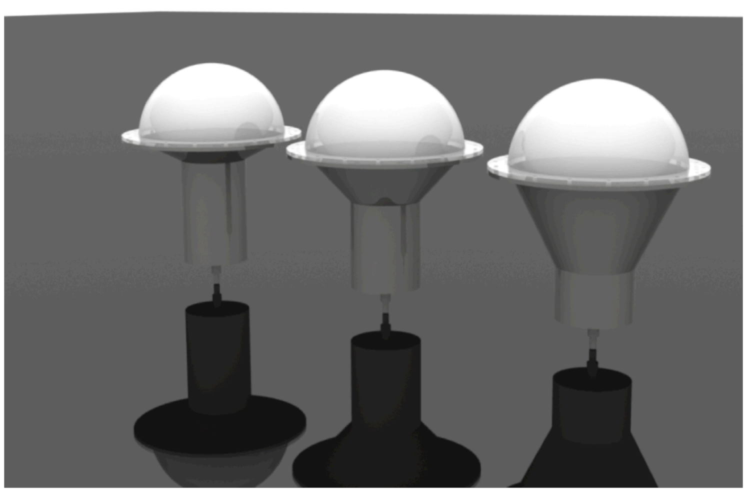
<u>Cylindrical encapsulation:</u>
Steel: 0.5mm thickness, 2.61kg
Acrylic glass: 2mm thickness, 0.22kg
Total surface: $0.46 m^2$



Pressure withstanding PMT encapsulations for LENA

Pressure simulation results: ETEL 9354 (8“)





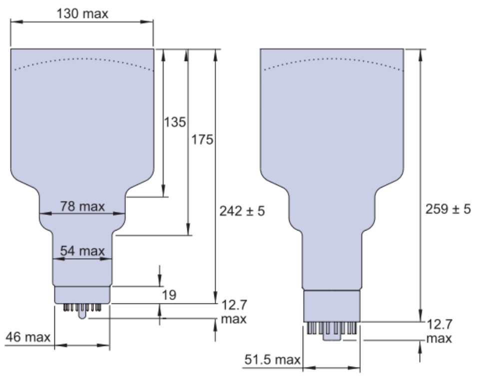
- For R5912 (8“) conical encapsulation was most promising ⟶ detailed study for this type for ETEL 9354
- Minimize weight in dependance of height of conical section
  - Thickness steps reduced to 0.1mm, for most lightweight encapsulation 0.01mm
  - Weight minimal for maximum length of conical part

Height of conical section [mm]	Minimal steel mass [kg]	Minimal acrylic glass mass [kg]	Total surface [m²]
33	3.45	0.44	0.535
54	3.20	0.43	0.534
70	3.14	0.43	0.535
130	2.94	0.43	0.549

<u>Conical encapsulation:</u>
Steel: 0.45mm thickness, 2.94kg
Acrylic glass: 2.40mm thickness, 0.43kg
Total surface: $0.55m^2$

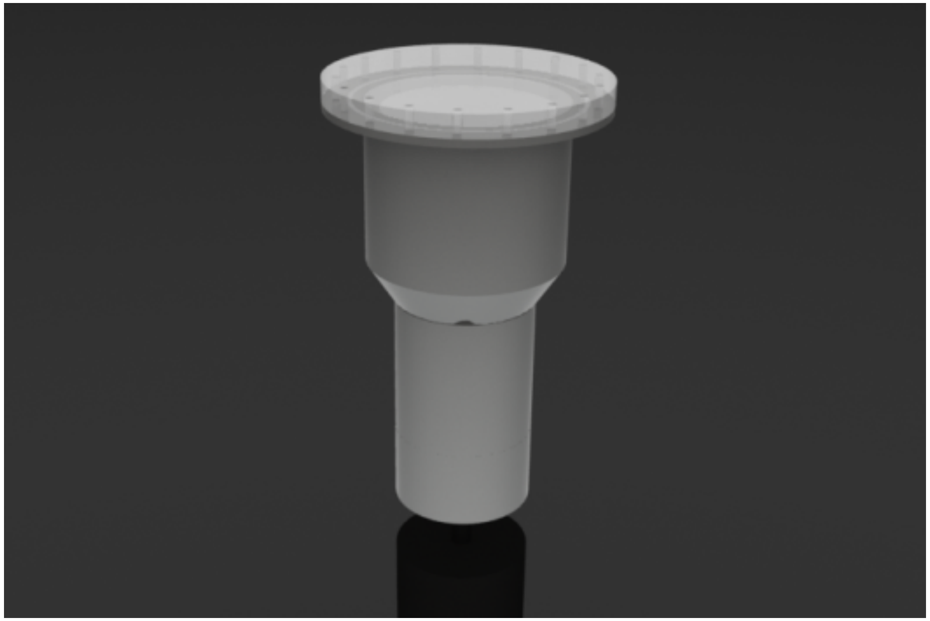
Pressure simulation results:

ETEL 9823 (5“)



- Plano-concave photo cathode → try flat acrylic glass window
- Very high thickness necessary

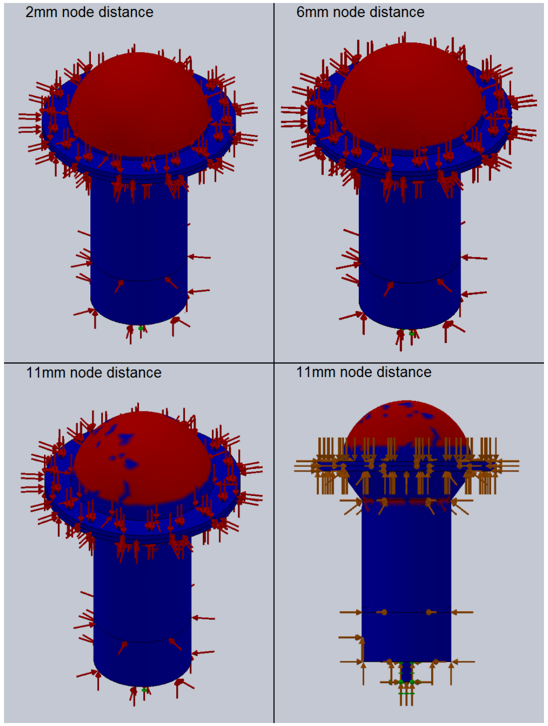
  → Probably less material for spherical acrylic glass window needed

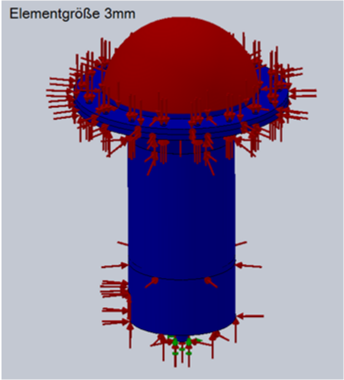


Conical encapsulation:	
Steel:	0.6mm thickness
Acrylic glass:	17mm thickness

Pressure simulations: cross-check of results

- Reproducibility
  - Repeated same simulation several times →
    - Same results
    - However only on fast computer - *results varied for slow computer!*
- Vary node distance from 2-11mm
  - No big change for 2mm → 3mm
  - For 11mm unphysical results
  - Where possible repeat simulation with 2mm to verify results





Factor of safety distribution: red areas are unstable (FoS <1)

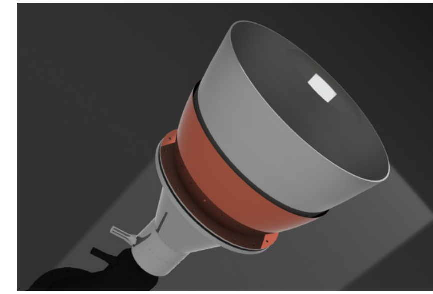
Next steps:

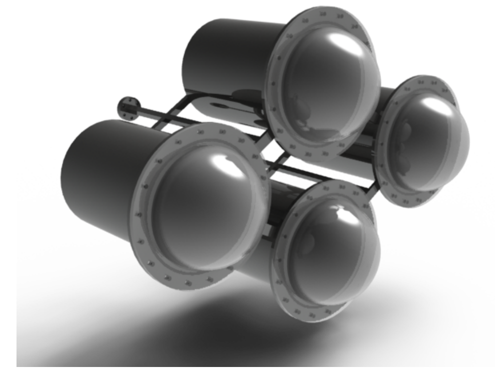
sign + simulations

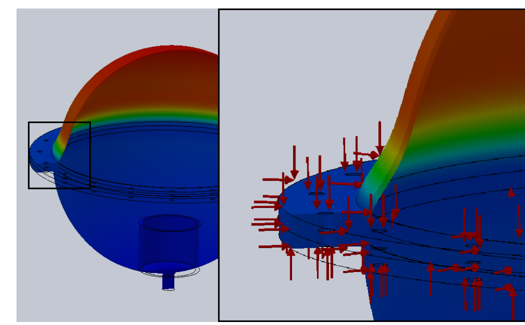
- Further crosschecks
- More exact simulations: reduce node distance (locally or globally), use adaptive methods
- Complete design (fixture for PMT inside encapsulation, filling valve) + create complete optical module: incorporate Mu-metal, Winston Cones, connections to other PMTs + wall
- Optimize encapsulations for least weight + least production costs
- Create + simulate designs for further PMTs (R6091, 9822, R11780, D784)
- Distortion analysis
- Aging simulation

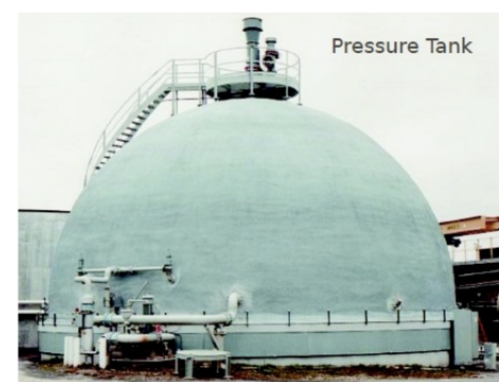
Build + test Prototypes

- Build prototype for PMT of choice
- Test in pressure tank
  - Adapt design to meet requirements
  - Influence of PMT implosion on adjacent encapsulations









Pressure encapsulations

- Are they necessary?

- New PMTs being developed for LBNE:
  - Designed for 11bar (81m tank height) + good performance, will have housing around pins (most sensitive area)
  - Hamamatsu R11780: 12“
    - Designed from scratch
    - Two independent simulations by Hamamatsu + LBNE ⟶ fulfills pressure requirements
    - ≈100 prototypes build ⟶ sensor properties look mostly very good by now, will commence pressure tests soon
    - Did pressure tests for R7081 (10“): designed for 7bar, all survived until 10bar, some above 15bar
  - ETEL D784: 11“
    - Designed from scratch
    - Simulations ⟶ fulfills pressure requirements
  - Both manufacturers claim that designs for higher pressure should be possible, problem is not pressure but pressure + high purity water for several 10y

- ***LENA: Do we need pressure encapsulations: for the ID? for the OD?***
  - ID (100m height): LAB ⟶ ≈9.8bar
  - OD (100m height): water ⟶ ≈11bar + ultrapure water for 30y
    a) Use encapsulations
    b) Develop new PMT type which can withstand 13+bar
    c) Decrease height

- ***Is it an option to incorporate the buffer <u>into</u> pressure encapsulation?***

Light concentrators

- First simulations: Winston Cones with ≈49° opening angle → area increase ≈1.75x seem most promising:
  - Field of view limitted to FV → reduce ratio scattered photons/ detected photons
  - Overall increase of p.e. yield due to larger input aperture → could reduce number of PMTs needed for same p.e. yield
- However: Complete MC of detector response→ effective area inrease by use of Winston Cones is much smaller than the mathematical one:

  For 50° opening angle:
  - Mathematical area increase =1.70
  - Effective area increase ≈1.28

Borexino Winston Cone

Adapt PMT numbers in White Paper accordingly?
Yes! But what are the correct numbers?

- Problem: effective area increase depends on length of optical module (not included in simulations yet)
- Length not yet known (can be estimated though)
- Length depends on PMT diameter
- Need to repeat simulations with varying lengths → time-consuming

Summary

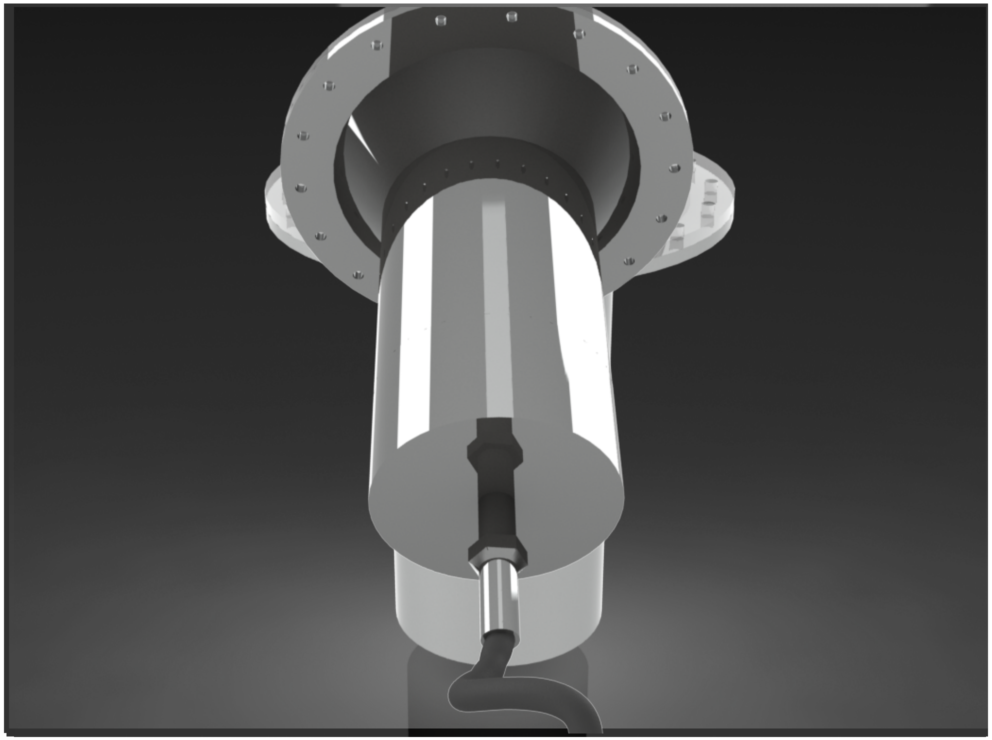
- Photosensor choice:
  - Have started to determine influence of photosensor properties on detector performance with Geant4 Monte Carlo
  - Photosensor test facility in Munich can soon take measurements
  - SiPMs have too high dark count for use with standard trigger configuration $\longrightarrow$ reanalyze using local triggers
  - Some other promising alternative sensors have to be tested
  - So far PMTs favoured option
- Development of PMT optical module:
  - Have completed first designs + FEA simulations of pressure encapsulations $\longrightarrow$ optimize designs, cross-check simulation results
  - Light concentrators apparently have much lower effective area increase $\longrightarrow$ possible reduction of PMT number smaller as expected

Possible topics for discussion

- White Paper:
  - Update numbers to a FV of 50kt?
  - LAB as favored scintillator?
  - Photosensors:
    - Increase requirements on dynamic range?
    - Already possible to update dark count requirements?
    - Eliminate SiPMs as option from White Paper / update usability?
    - Effective area increase of Winston Cones: Correct numbers of PMTs needed?
- Pressure requirements:
  - Use encapsulations? In ID? In OD?
    - Incorporate buffer into pressure encapsulation?
  - Use LBNE PMT types $\longrightarrow$ tank with decreased height + increased diameter?
- Until when has the the photosensor type to be chosen?

Backup slides

Assembly of a R6594 conical encapsulation



- Assembly sequence for conical encapsulation:
  1. Solder voltage divider circuit board to socket for PMT pins
  2. Insert into lower part of metal encapsultion / plastic housing
  3. Infuse polyurethane → fixes VD + socket
  4. Bolt down upper part of metal encapsulation + retaining ring to hold down PE
  5. Insert PMT into socket
  6. Attach acrylic glass window (using o-ring seal) + brackets connecting PMTs to modules and attaching them to the walls
  7. Fill up encapsulation with oil

Attachment to wall