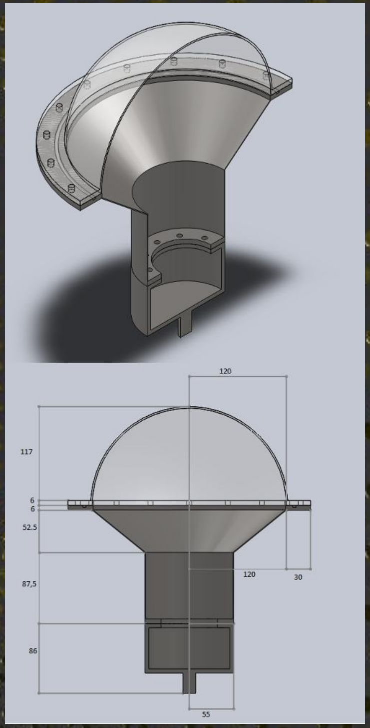
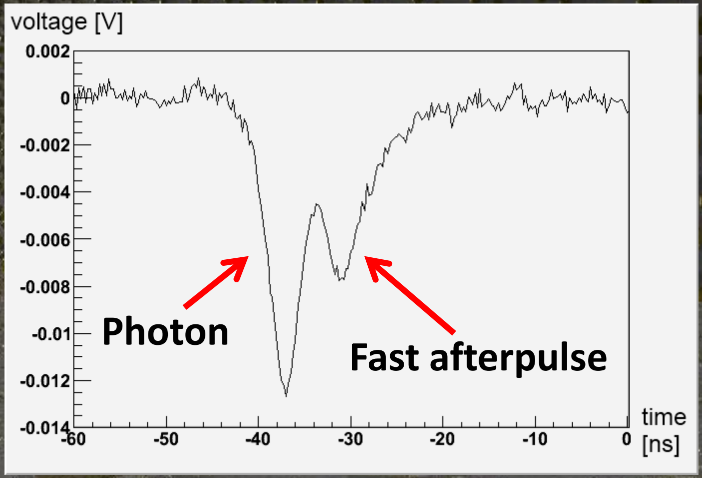
Design and FEA simulations of pressure withstanding PMT encapsulations for LENA

and

Algorithms to identify fast afterpulses on a previous pulse





Marc Tippmann

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Light2011, Ringberg
2011/10/31

Overview

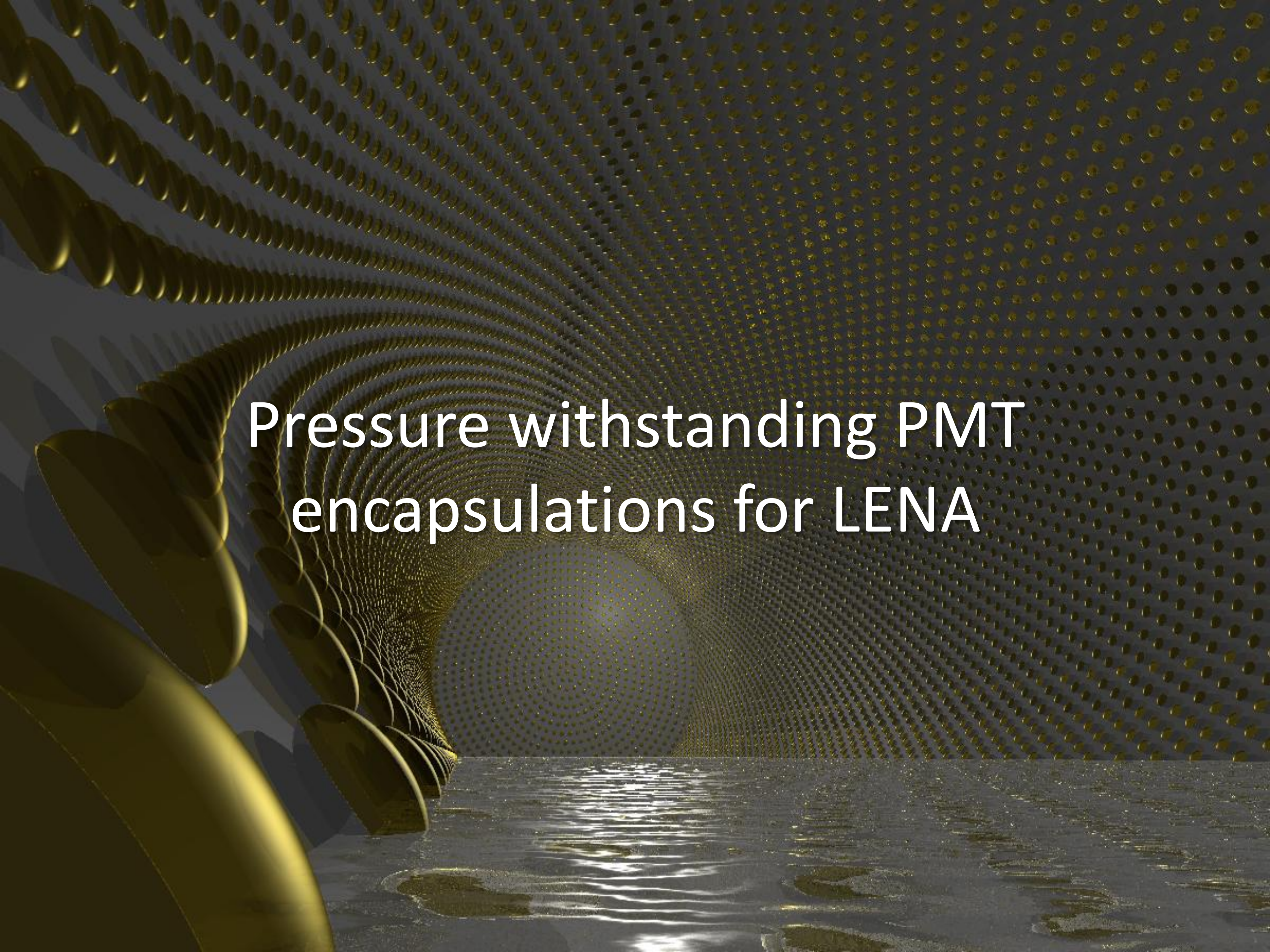
Pressure withstanding PMT encapsulations for LENA

- Why encapsulate PMTs?
- Design
- Finite Elements Analysis simulations + results
- Next steps

Fast Afterpulses in PMTs + SiPMs

- Causes
- Reasons to study them
- Algorithms to detect fast Afterpulses on the flank of a previous pulse

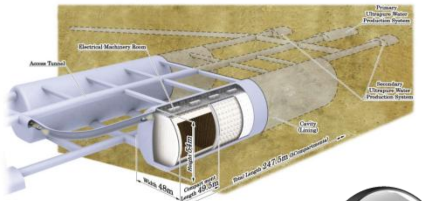
Summary

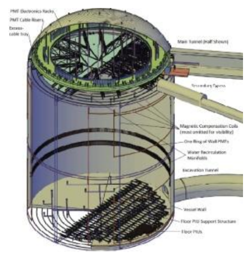


Pressure withstanding PMT encapsulations for LENA

Pressure withstanding PMT encapsulations for LENA: Why encapsulate PMTs?

HyperK
Hyper-Kamiokande detector





LBNE LENA

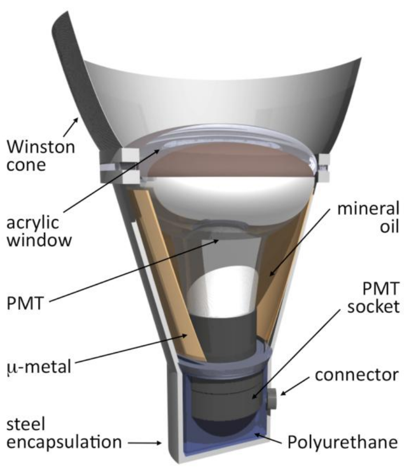
- Next-generation land-based neutrino experiments like HyperK, LBNE or LENA use tanks with heights of 50-100m

  ⟶ High pressure at the tank bottom

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

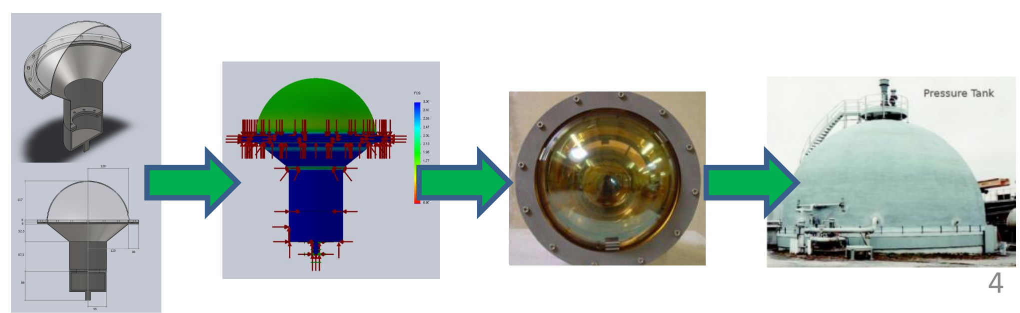
  ⟶ At the moment no available PMT model fulfills requirements

- 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

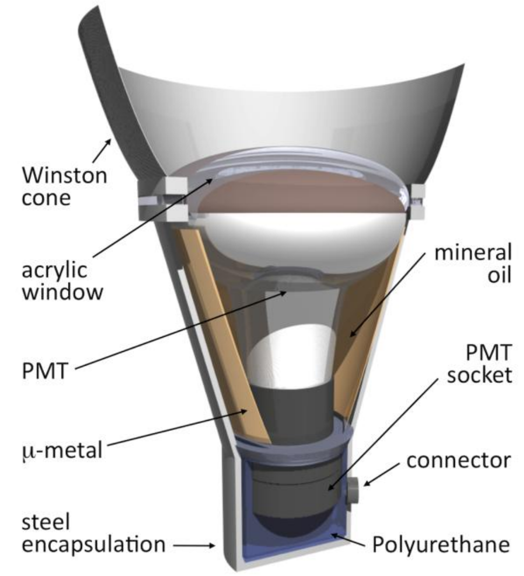


How to develop an encapsulation?

- *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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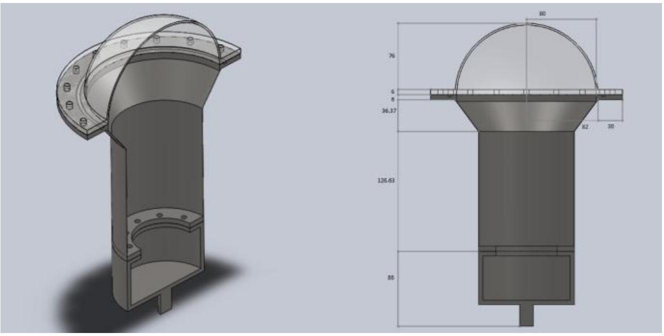
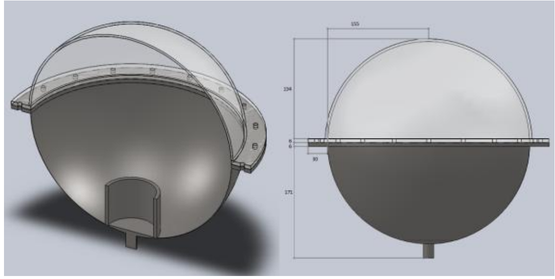
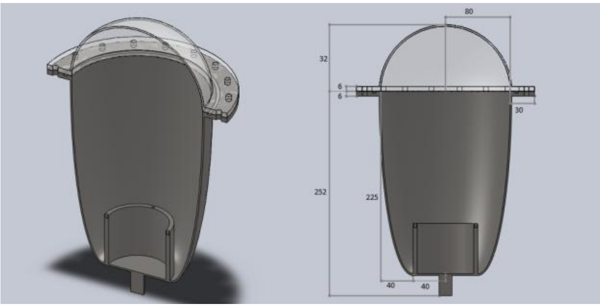
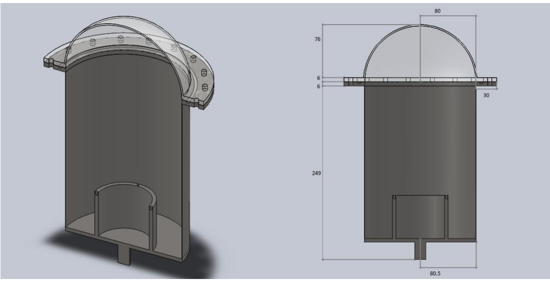








Pressure withstanding PMT encapsulations for LENA:
Pressure simulations

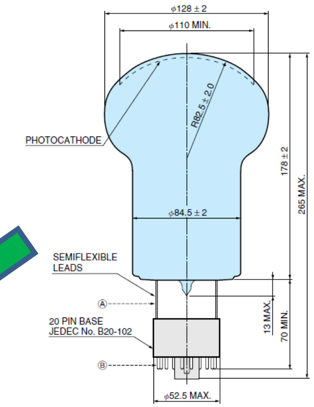
- Simulate behaviour under pressure with a Finite Elements Analysis (FEA) simulation software
  – Engineering drawings and FEA pressure simulations were done with same software
- Software: SolidWorks Educational Edition Academic Year 2010-2011 SP4.0, *Simulation Premium package*
- Settings: Linear static 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!*

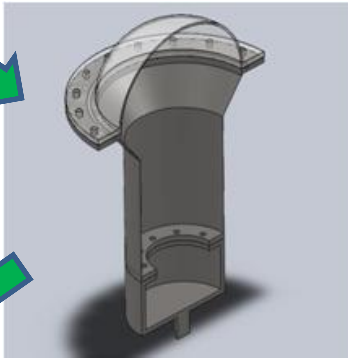
Pressure withstanding PMT encapsulations for LENA:

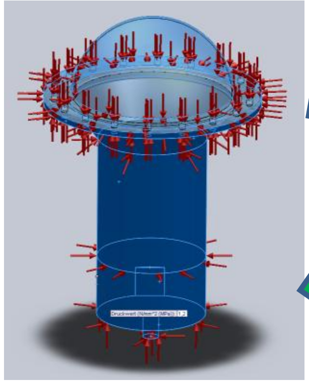
Pressure simulations

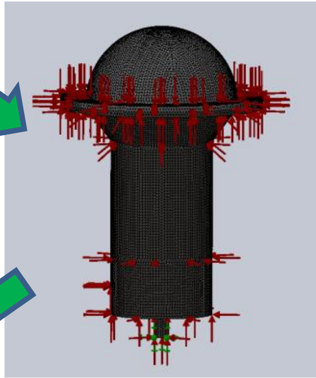


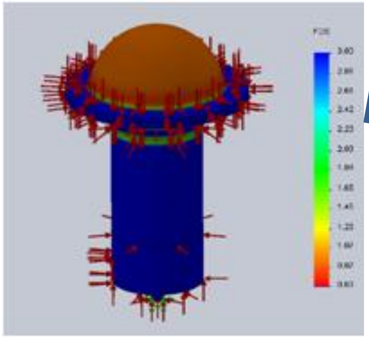
Procedure:

- 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



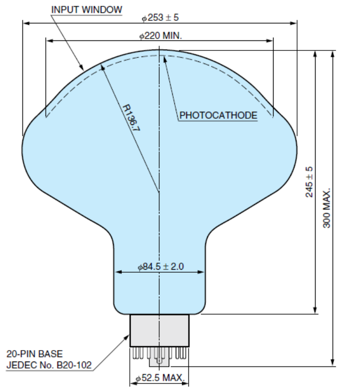


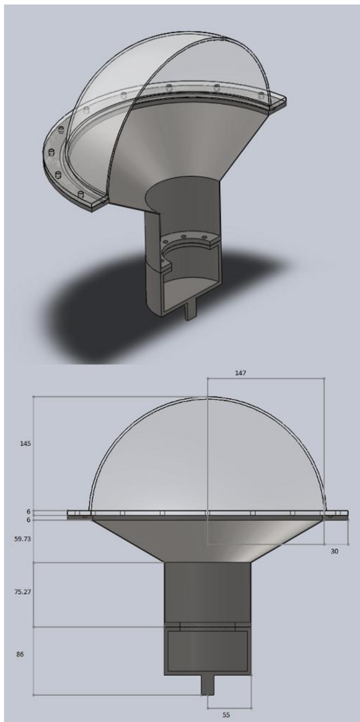


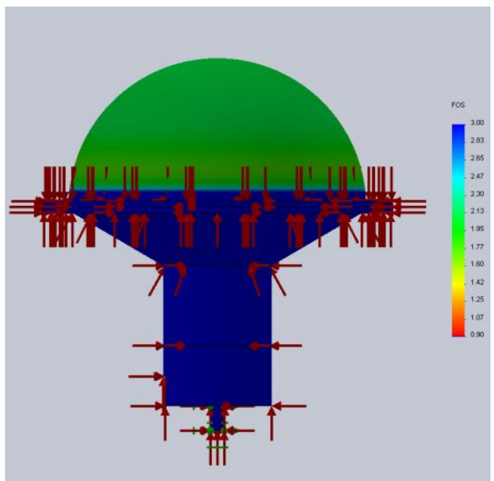


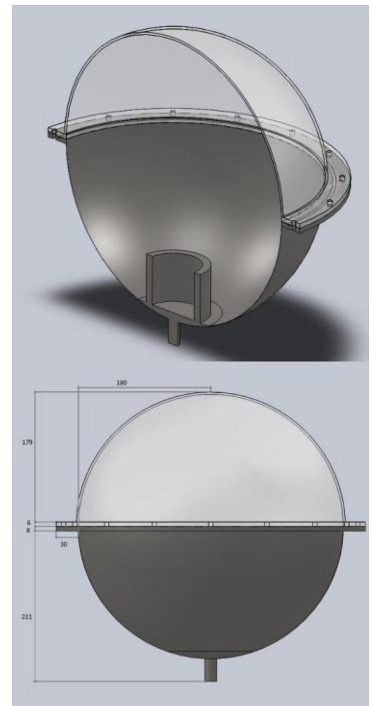
Pressure withstanding PMT encapsulations for LENA

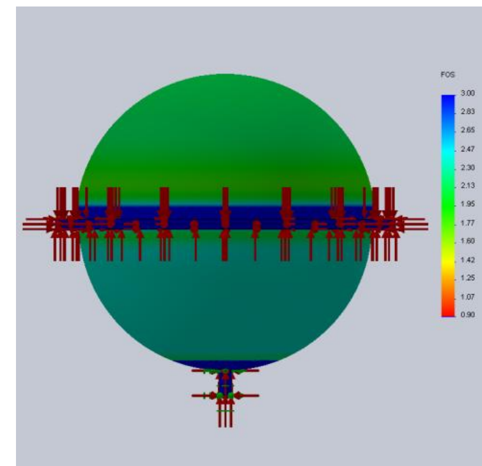
Pressure simulation results: Hamamatsu R7081 (10“)











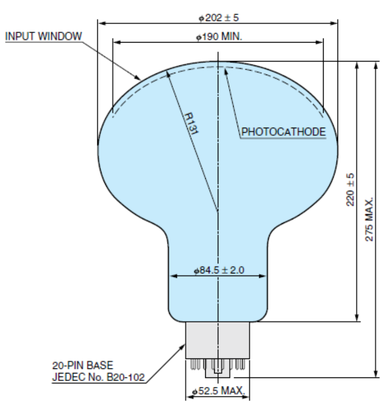
<u>Conical encapsulation:</u>

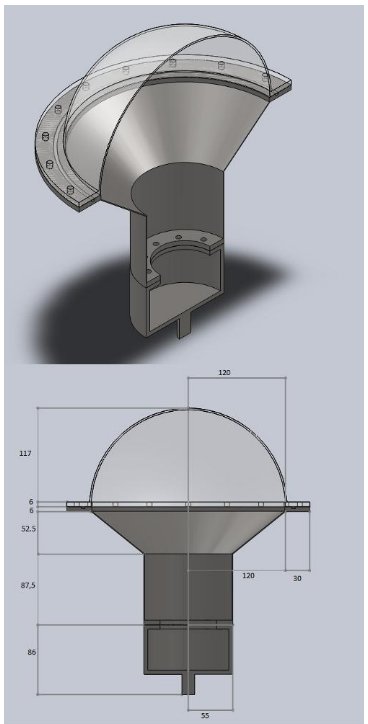
Steel:	2mm thickness,	4.38kg
Acrylic glass:	4mm thickness,	0.86kg
Total surface:	0.69m²	

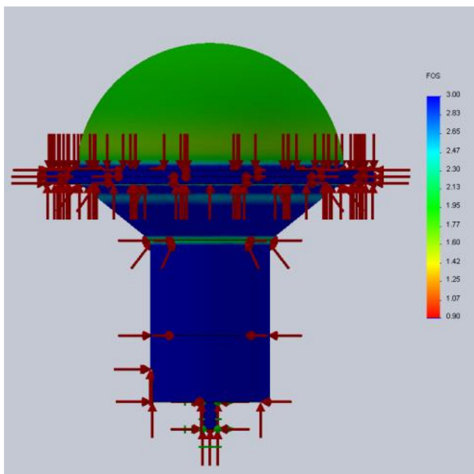
<u>Spherical encapsulation:</u>

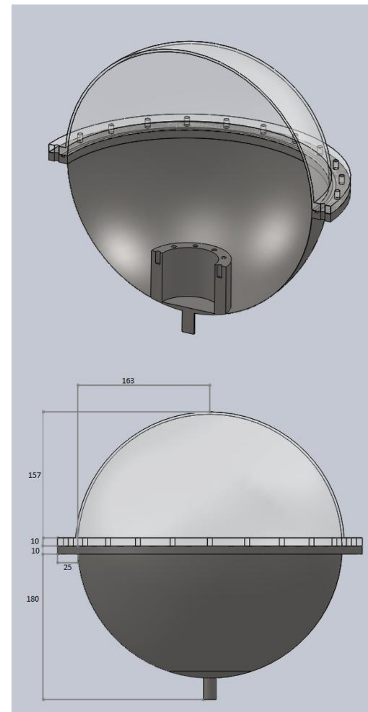
Steel:	0.5mm thickness,	4.08kg
Acrylic glass:	5mm thickness,	1.48kg
Total surface:	1.01m²	

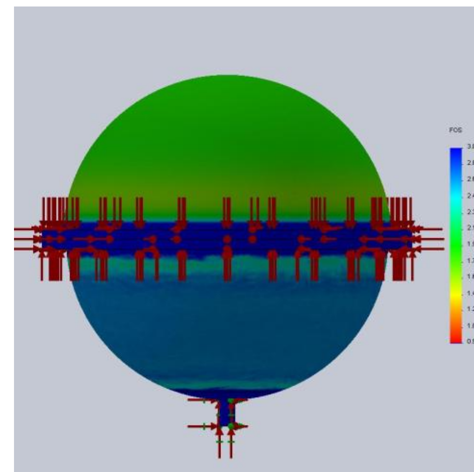
Pressure simulation results: Hamamatsu R5912 (8")











<u>Conical encapsulation:</u>

Steel: 1mm thickness, 3.24kg

Acrylic glass: 3mm thickness, 0.50kg

Total surface: 0.53m²

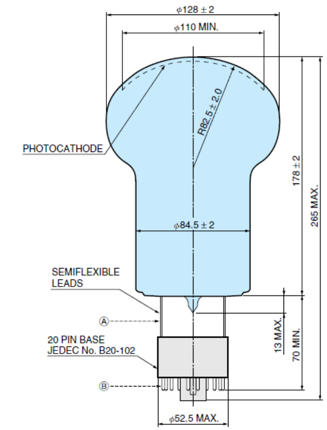
<u>Spherical encapsulation:</u>

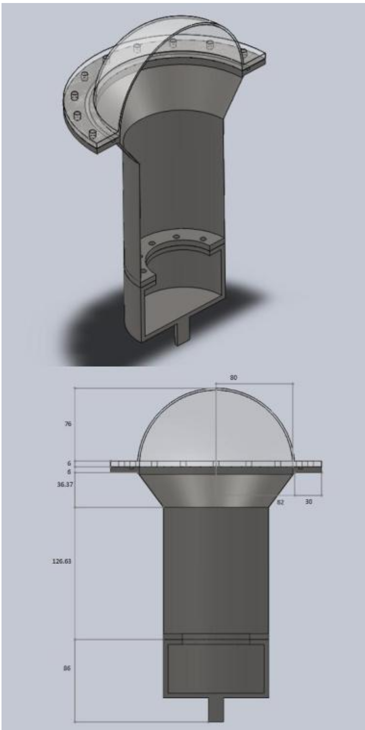
Steel: 0.5mm thickness, 4.66kg

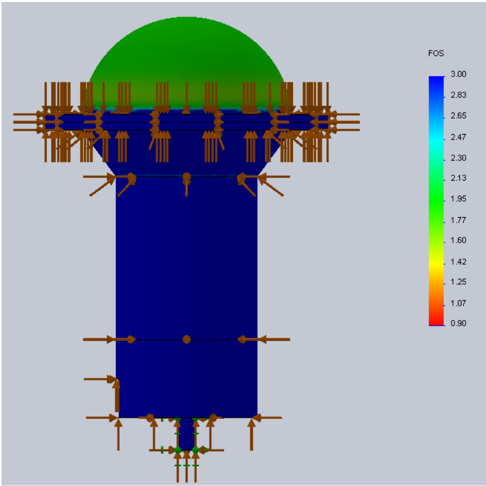
Acrylic glass: 4mm thickness, 1.10kg

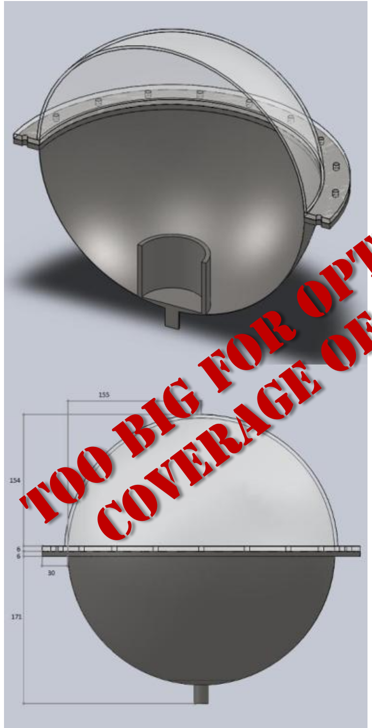
Total surface: 0.83m²

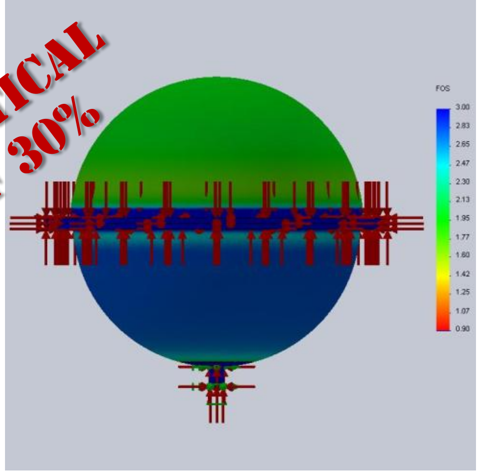
Pressure simulation results: Hamamatsu R6594 (5“)











TOO BIG FOR OPTICAL COVERAGE OF 30%

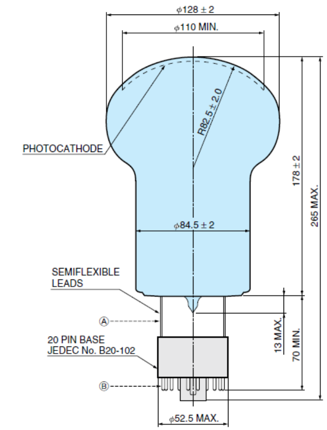
<u>Conical encapsulation:</u>

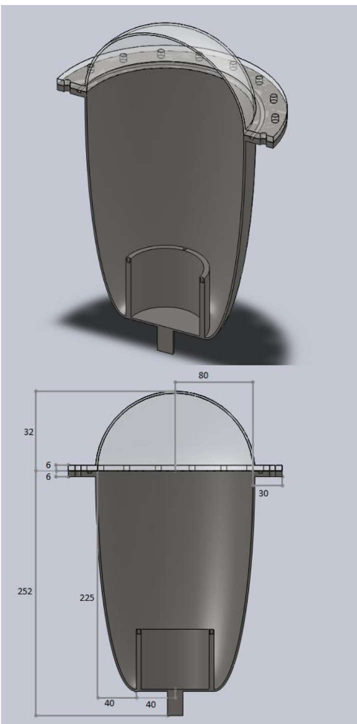
Steel:	1mm thickness,	2.77kg
Acrylic glass:	2mm thickness,	0.22kg
Total surface:	0.37m²	

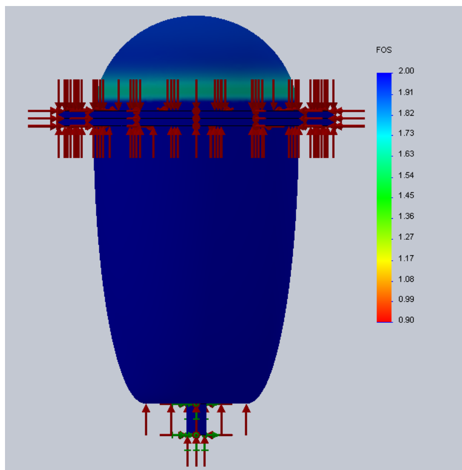
<u>Spherical encapsulation:</u>

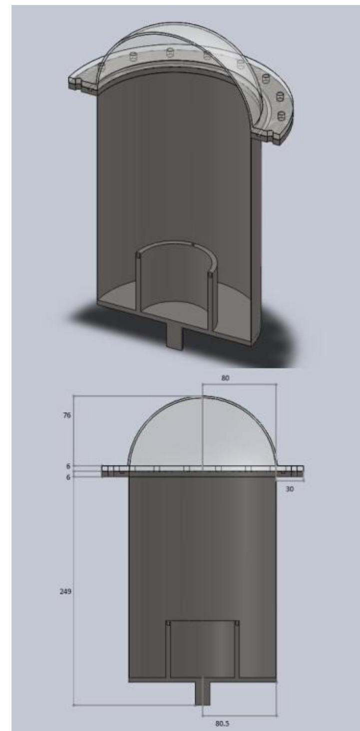
Steel:	0.5mm thickness,	2.75kg
Acrylic glass:	4mm thickness,	0.94kg
Total surface:	0.78m²	

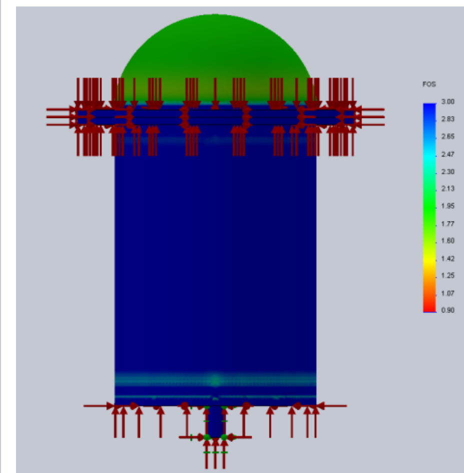
Pressure simulation results: Hamamatsu R6594 (5“)









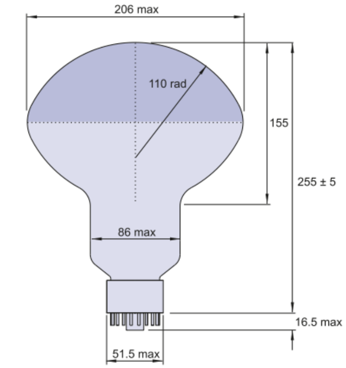


Elliptical encapsulation:

Steel:	2mm thickness,	3.06kg
Acrylic glass:	2mm thickness,	0.22kg
Total surface:	0.41m²	

Cylindrical encapsulation:

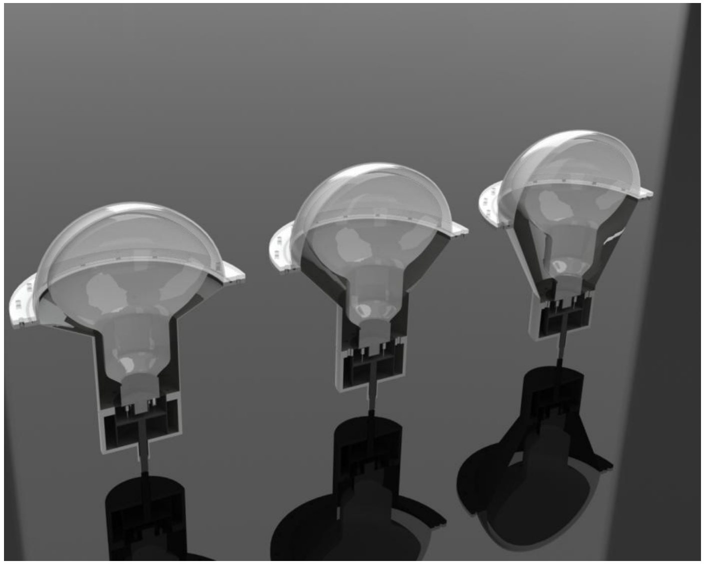
Steel:	0.5mm thickness,	2.61kg
Acrylic glass:	2mm thickness,	0.22kg
Total surface:	0.46m²	



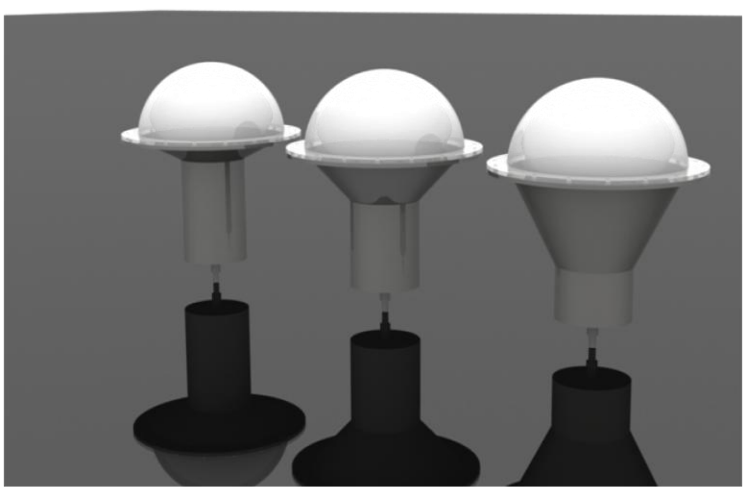
Pressure withstanding PMT encapsulations for LENA

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

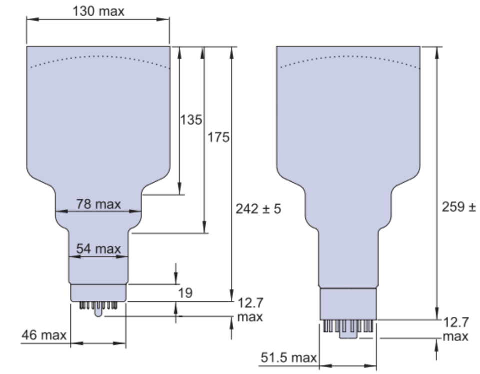


Height of conical section [mm]	Minimal steel mass [kg]	Minimal acrylic glass mass [kg]	Total surface [m²]
33	3.45	0.44	0.535
54	3.20	0.43	0.534
70	3.14	0.43	0.535
130	2.94	0.43	0.549



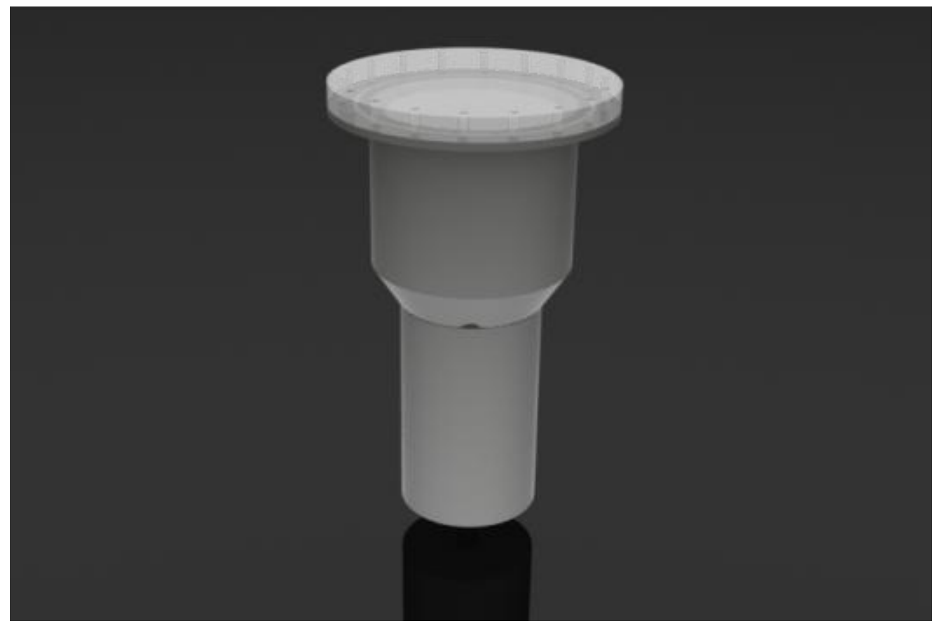
Conical encapsulation:
Steel: 0.45mm thickness, 2.94kg
Acrylic glass: 2.40mm thickness, 0.43kg
Total surface: 0.55m²

Pressure simulation results: ETEL 9823 (5")



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

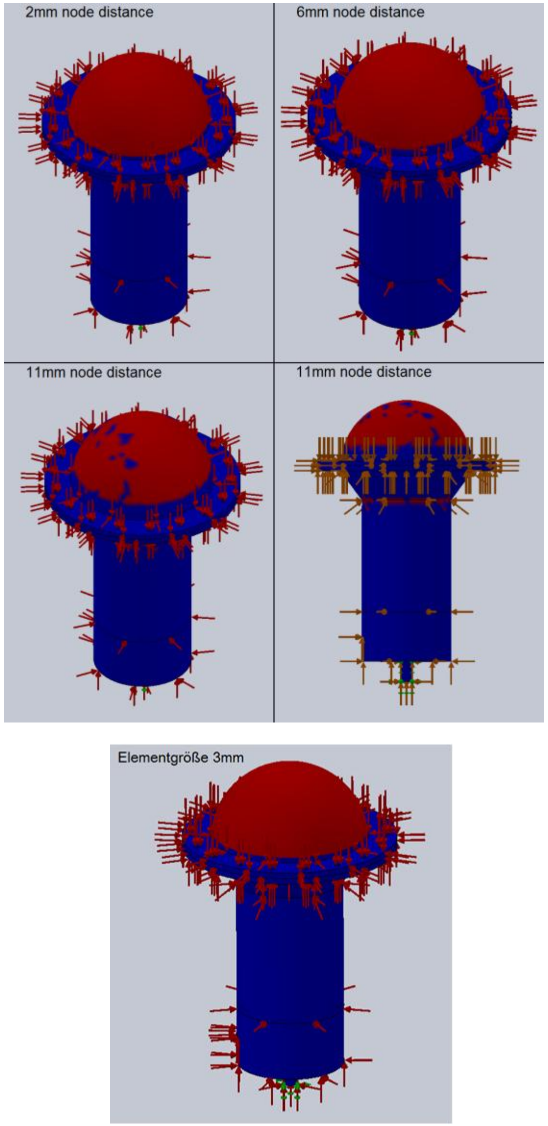
  → Probably less material for spherical acrylic glass window needed



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

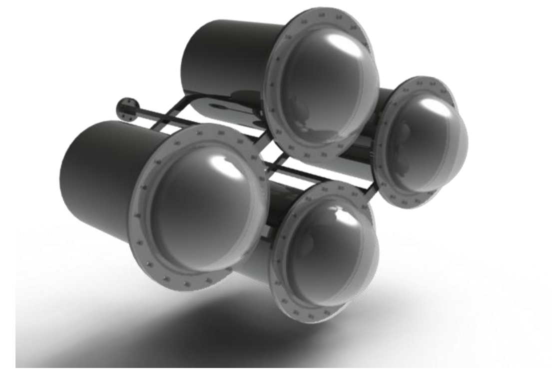
Pressure simulations: cross-check of results

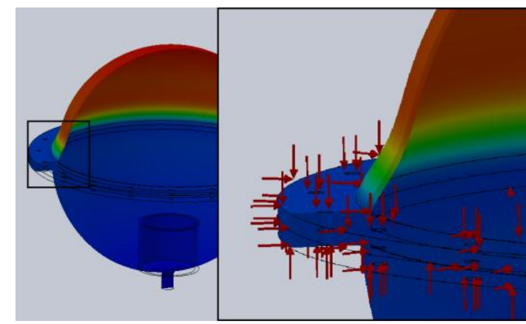
- Reproducibility
  - Repeated same simulation several times →
    - Same results
    - However only on fast computer - *results varied for slow computer!*
- Vary node distance from 2-11mm
  - No big change for 2mm → 3mm
  - For 11mm unphysical results
  - Where possible repeat simulation with 2mm to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



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

Next steps:



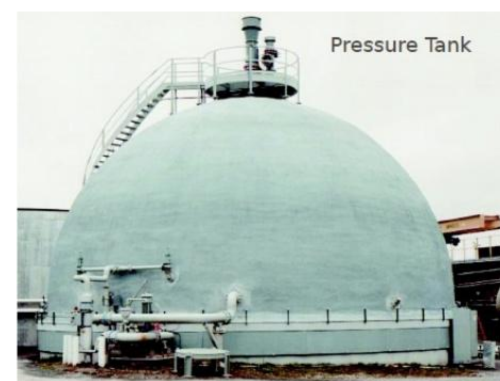


DESIGN + SIMULATIONS

- 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

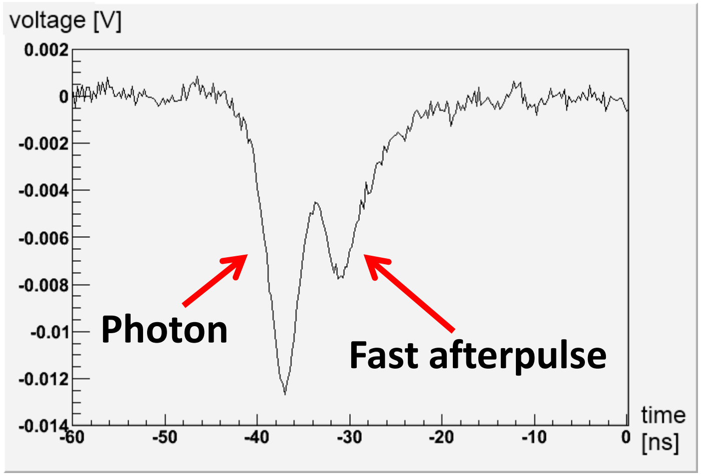
- Build prototype for PMT of choice
- Test in pressure tank
  - Adapt design to meet requirements
  - Influence of PMT implosion on adjacent encapsulations



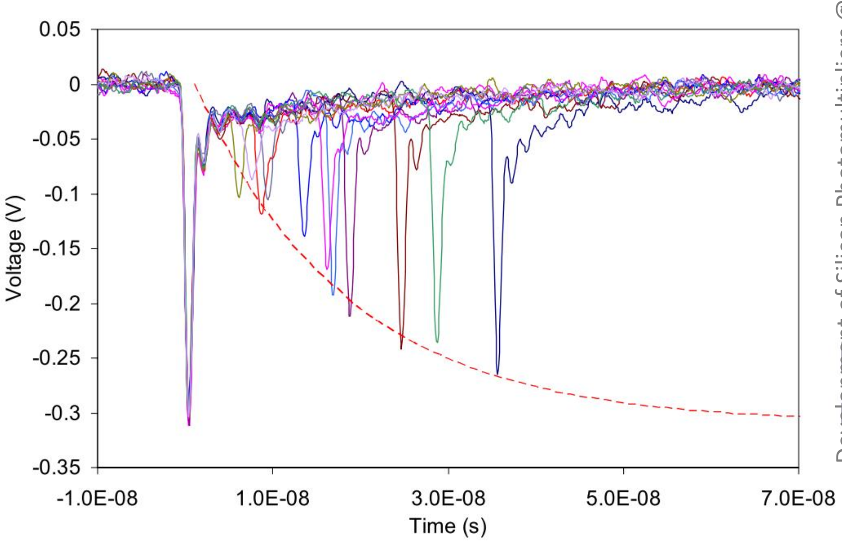
Fast Afterpulses in PMTs and SiPMs

Fast Afterpulses (fAP): Causes

- Additional pulse(s) occurring after a previous pulse within several 10 ns
- Occur in PMTs as well as SiPMs
- Possible causes:
- PMTs:
  - Light generation in PMT:
    - Bremsstrahlung at dynodes → delay ≈ ½-1 transit time (tt)
    - Ionization / excitation
      - of residual gas molecules near anode → delay ≈ 1tt
      - of molecules/atoms on dynodes (adsorbed/constituents) → delay ≈ ½-1tt
  - Partial inelastic scattering of photo electron on first dynode then elastic scattering → delay ≈ 0-1tt
- SiPM:
  - charge trapping, release time constant ~ 10-100ns



Fast Afterpulse in PMT



Fast Afterpulses in SiPM

Development of Silicon Photomultipliers @ IRST, Claudio Piemonte, FNAL, 2006

Fast Afterpulses (fAP):
Reasons to study them

- Detectors using PMTs/SiPMs: fAP influence
  - Energy resolution
  - Event reconstruction: position + time resolution, tracking
  - SiPM: with increasing overvoltage PDE, fAP probability and cross-talk increase

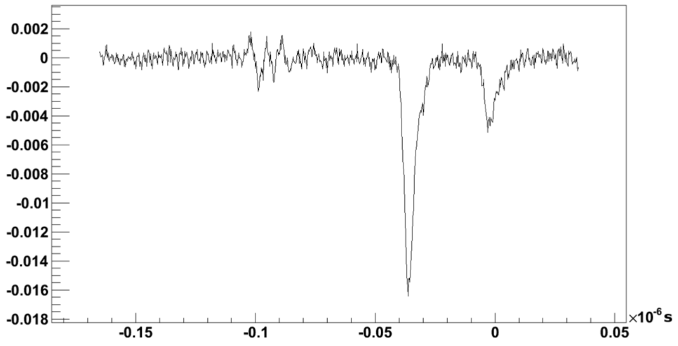
    → Lose single photon resolution for several photons incident at same time

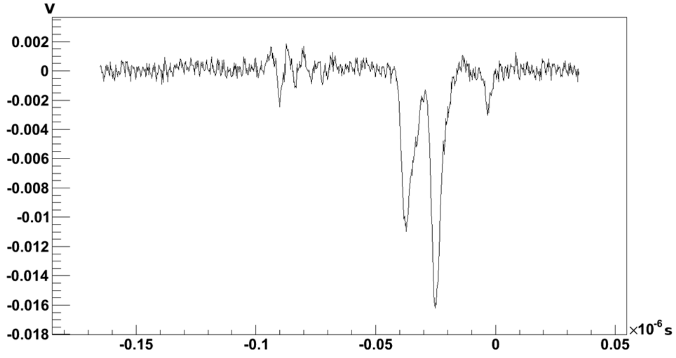
    → Tradeoff between PDE and energy resolution necessary

  → To be able to reduce fAP probability study fAP to understand mechanisms of production better

- To be able to analyze them first need to identify all fAP in recorded pulses
  - Easy for fAP occurring after end of original pulse
  - Difficult for fAP sitting on flank

    → Need detection algorithms to study them





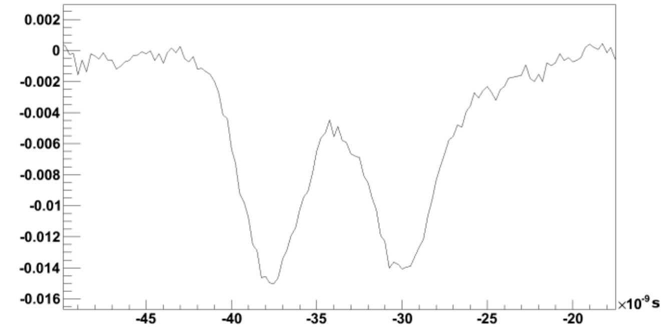
Fast Afterpulses (fAP):

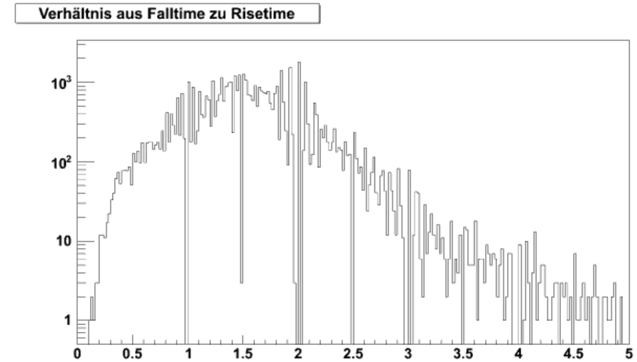
Algorithms to detect fast Afterpulses on the flank of a previous pulse

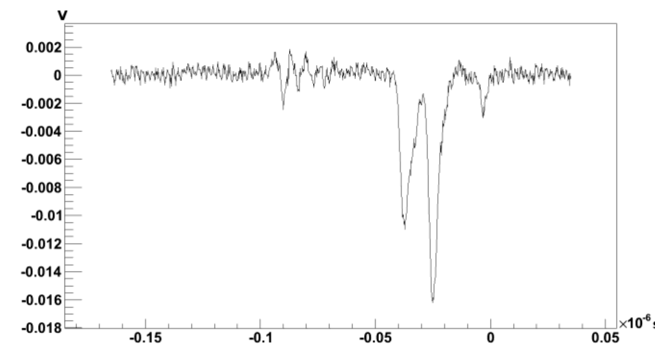
- Used 50000 pulses to develop algorithms
  - Instrumentation:
    - Light source: Edinburgh Instruments EPL-405-mod, 50ps FWHM diode laser, 403nm
    - PMT: ETL 9305 (+1300V), ≈5.5% detected pulses/laser trigger → ≈2.75% 2-photon-pulses for pulses with laser-PMT coincidence
    - FADC: Acqiris DC282, used 2Ch with 4GHz sampling, 10bit
  - Sampled 1500 pulses by eye →
    - ≈4.9% fAP on flank of main pulse
    - ≈2.1% after main pulse within 70ns
- Different classes based on recognition criteria:
  - Time
  - Pulse shape
  - Area
- *Was treated in a Bachelor thesis by* ***Martin Zeitlmair***

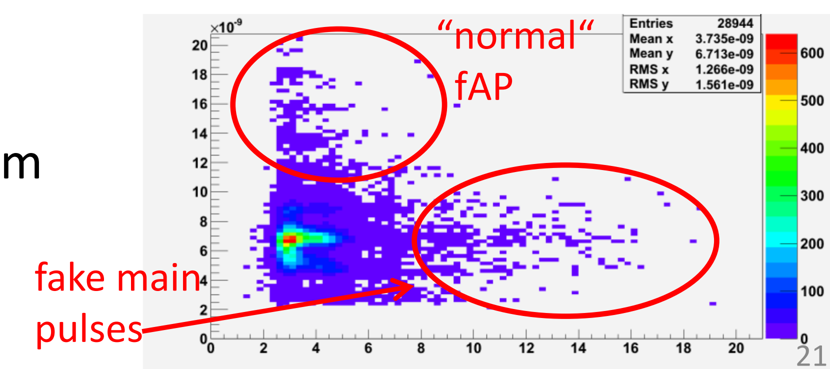
Fast Afterpulses (fAP): Detection algorithms: Time

- Ratio fall time/rise time
  - Principle: fAP on falling flank → time until pulse falls below 10% of pulse height is increased
  - Problems:
    - Fake main pulses: if fAP maximum > main pulse maximum, fAP is detected as pulse maximum → ratio too low
  - Conclusion:
    - No strong separation visible
    - Can be used for big ratios
    - Use as cross-check after other algorithm for fake main pulses



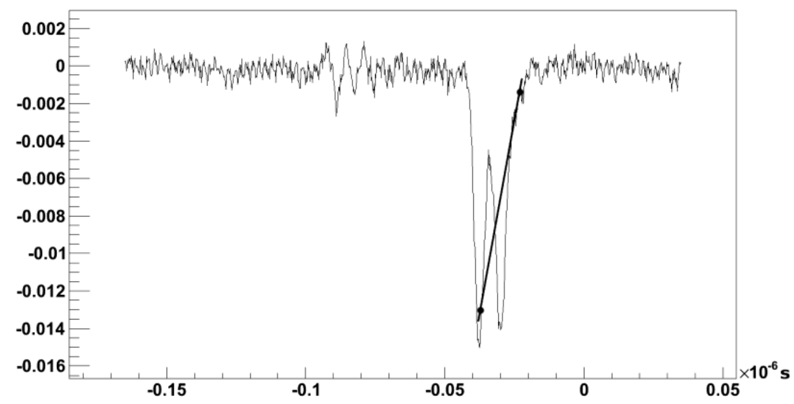


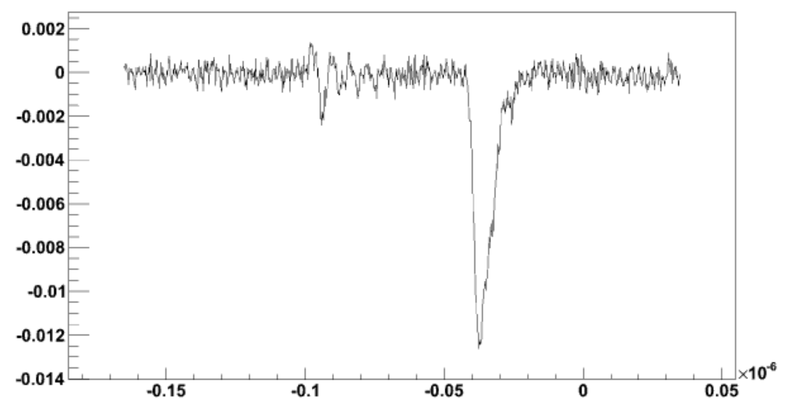




Fast Afterpulses (fAP):
Detection algorithms: Pulse shape

- Subtract pulse
  - Principle: subtract expected pulse shape on falling flank → fAP remain + can be found with simple threshold criterium
  - Model used for pulse shape
    - Linear interpolation: reliable, but low recognition rate
    - Parabola: low detection rate, problems with pulses with ≈linear decay: “bulgy“ pulses
    - Exponential decay: high recognition rate, but bulgy pulses filter through
    - Average pulse shape: same as exponential
  - Choose higher threshold for exponential decay / average pulse form

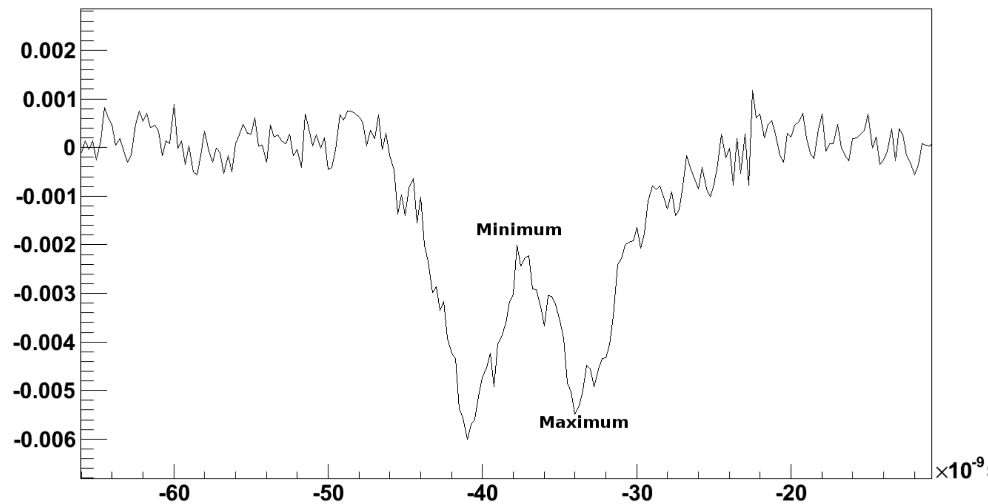




“Bulgy pulse“

Fast Afterpulses (fAP):
Detection algorithms: Pulse shape

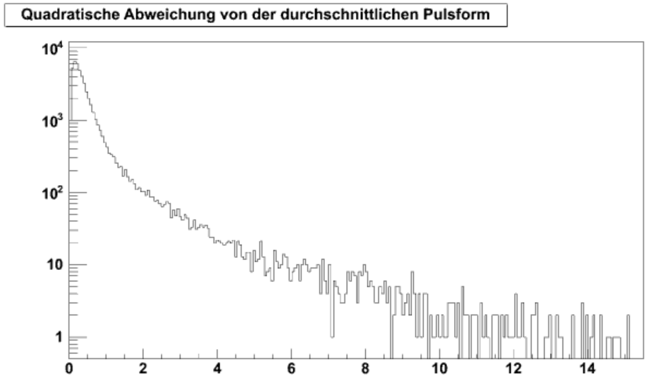
- Search maximum/minimum
  - Principle: fAP on falling flank produces an additional minimum + maximum
  - Methods:
    - Number of higher/lower points in interval around current point: bigger than threshold ⟶ extremum;
      - prone to noise



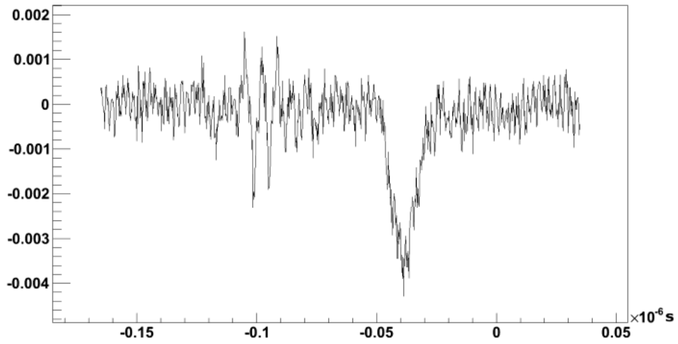
    - Three intervals: If maximum of interval 2 is bigger than maxima of interval 1+3 ⟶ peak found; more than one peak ⟶ fAP
      - Works very good for intervals with >3ns window
      - Next step: include threshold for height difference between minimum and fAP peak to be able to use smaller windows ⟶ find more AP which are small or close to peak

Fast Afterpulses (fAP): Detection algorithms: Pulse shape

- Search for inflection points
  - Principle: fAP on falling flank produces two additional inflection points → two additional zero crossings in 2nd time derivative
  - Problems: up to now jitter from noise too strong
  - Conclusion: need to average over more points

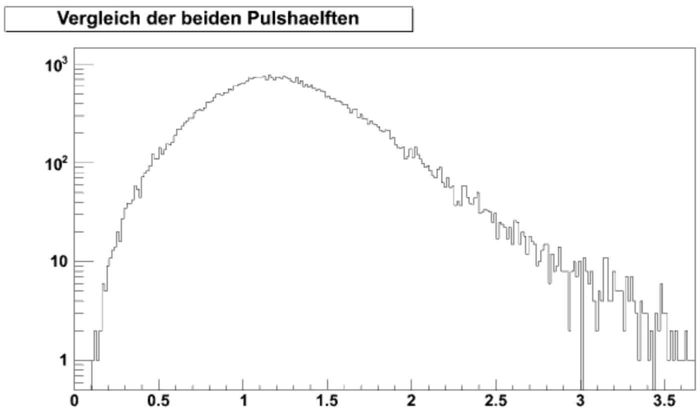


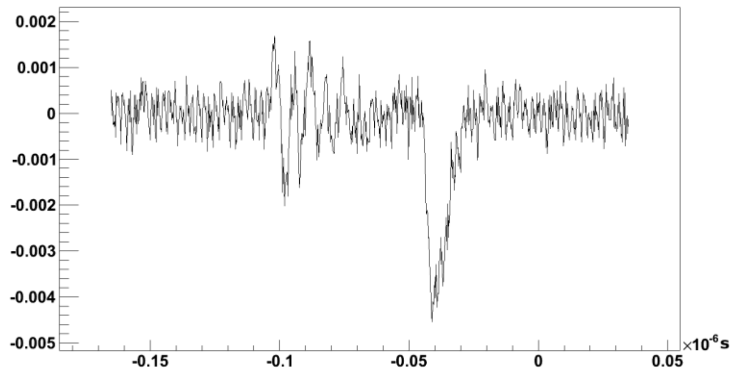
- Quadratic difference from average pulse form
  - Principle: integrate squared difference of pulse shape to average pulse shape for each data point; fAP on flank produce irregular pulse shape → higher value
  - Problems:
    - Pulses with small heights apparently have different shape + vary more strongly due to noise
  - Conclusion: should be usable for high values, use separate average pulse form for small pulses



Fast Afterpulses (fAP): Detection algorithms: Area

- Area ratio falling flank/rising flank
  - Principle: fAP on falling flank adds charge ⟶ time integral over falling flank gets bigger
  - Problems:
    - Fake main pulses ⟶ ratio too small
    - Bulgy pulses ⟶ higher ratios
  - Conclusion:
    - Usable for large ratios
    - For fake main pulses: use as cross-check after other algorithm





Summary

- Pressure withstanding PMT encapsulations for LENA:
  - Have designed engineering drawings of first encapsulations in CAD + simulated them with FEA software; method established → now refine it
  - Results still very preliminary, need to construct complete optical module and optimize for weight + costs before comparisons between different designs are possible
  - First results look promising
- Fast afterpulse detection algorithms
  - Developed several algorithms, identified problems
  - Still optimizing to eliminate disturbing effects and increase detection rate
  - With only small adjustments and combined evaluation of two methods, most algorithms should improve substantially

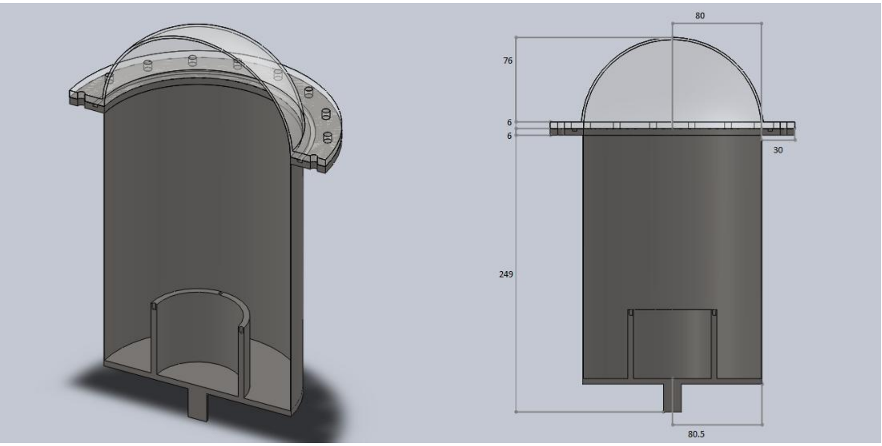
References

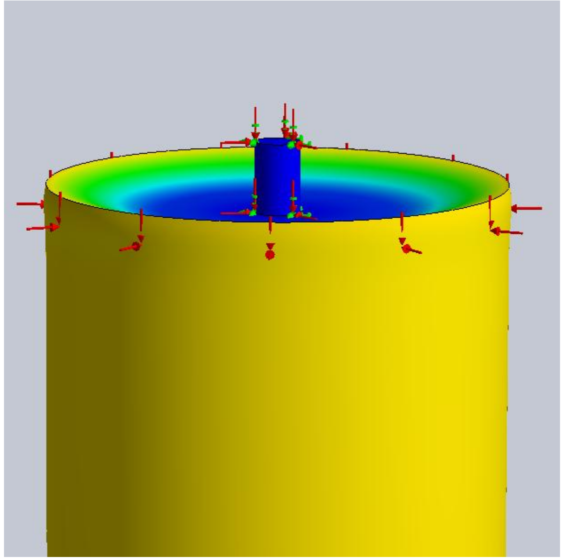
- For further information please refer to:

  - LENA White Paper, http://arxiv.org/abs/1104.5620
  - German Beischler, bachelor thesis, Technische Universität München, August 2011, http://www.e15.physik.tu-muenchen.de/fileadmin/downloads/thesis/bachelor/2011_BSc_German_Beischler.pdf
  - Martin Zeitlmair, bachelor thesis, Teschnische Universität München, July 2011, http://www.e15.physik.tu-muenchen.de/fileadmin/downloads/thesis/bachelor/2011_BSc_Martin_Zeitlmair.pdf

Backup slides

Cylindric encapsulation Hamamatsu R6594

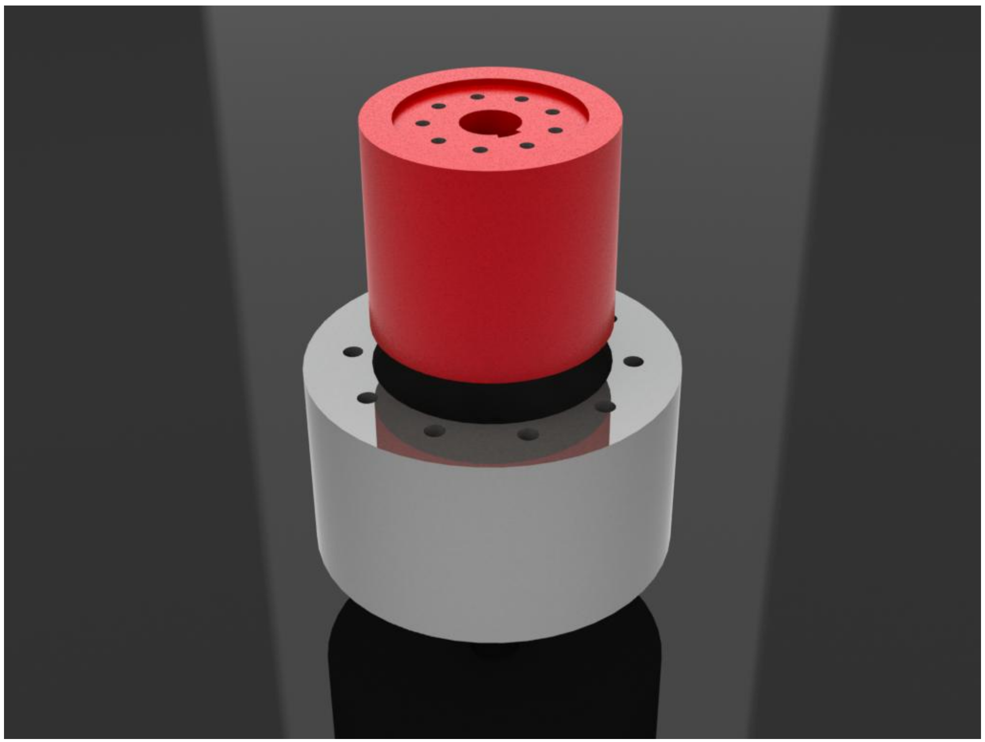




- Simple form
  - probably easy to produce + low costs
- Steel thickness 0.5mm

- Problem: floor was pushed in → tearing of side walls
  - First solution: enforced floor, however 5mm thickness needed
  - Optimize design: enforce walls in critical areas

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

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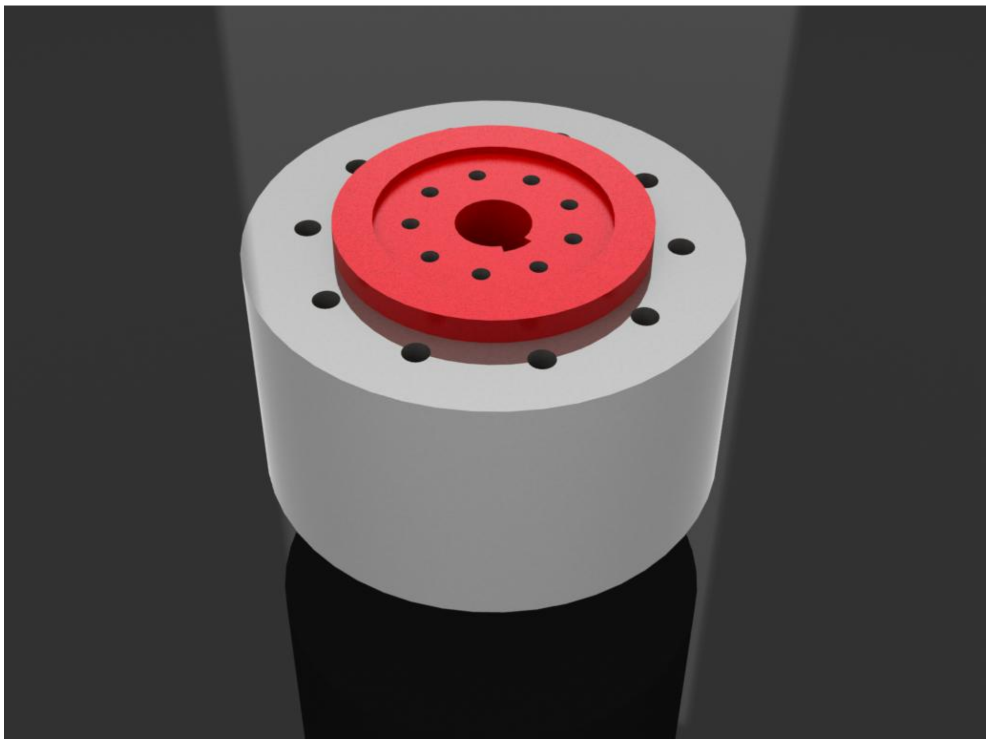

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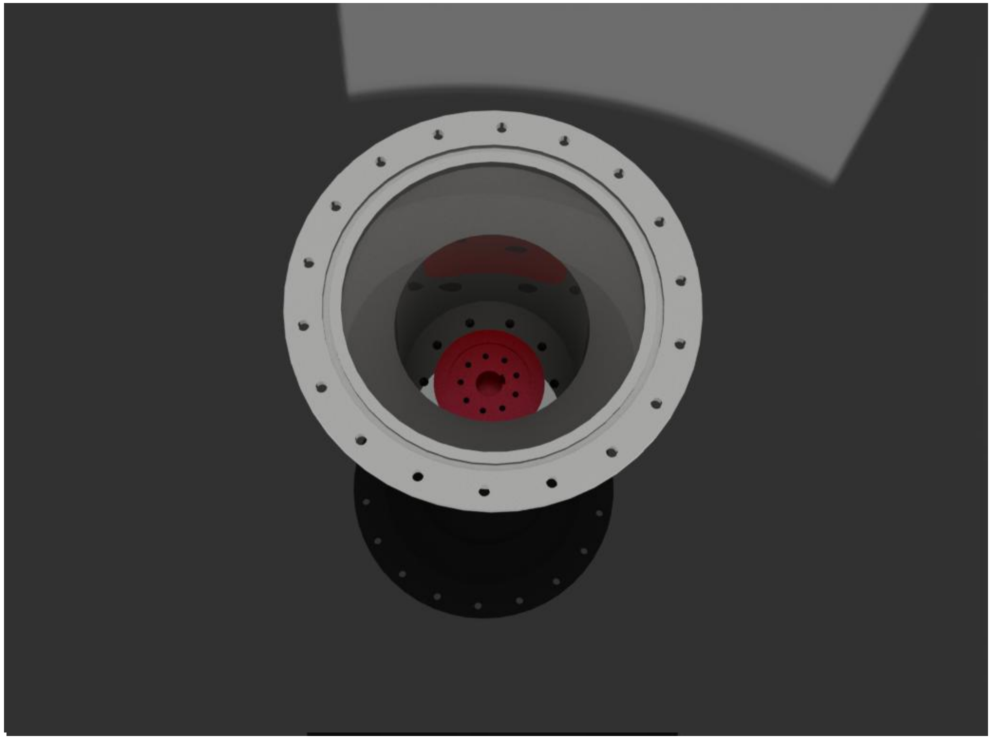

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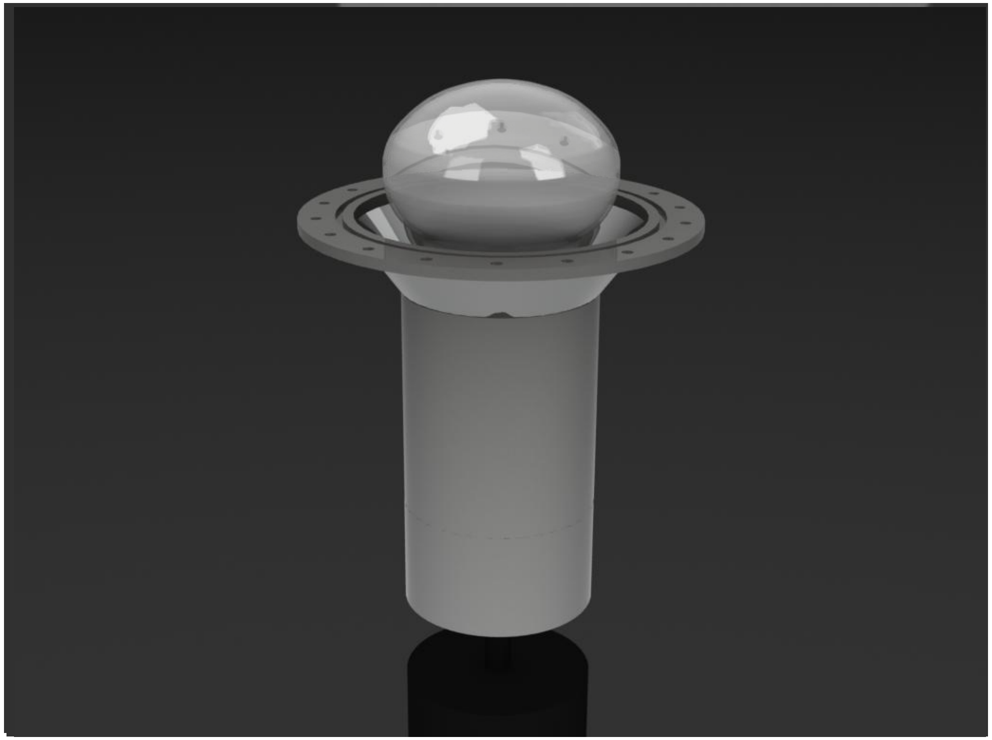

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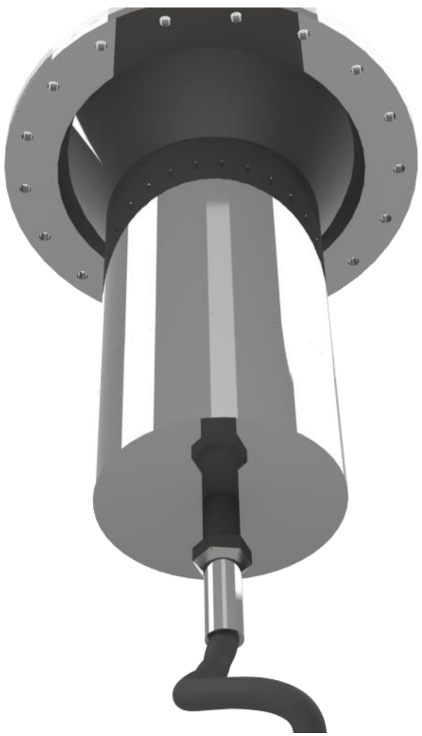

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Attachment to wall