Design and FEA simulations of pressure withstanding PMT encapsulations for LENA

and

Algorithms to identify fast afterpulses on a previous pulse

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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?

- 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*
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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“)

• 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“)

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

Spherical encapsulation:
Steel: 0.5mm thickness, 4.08kg
Acrylic glass: 5mm thickness, 1.48kg
Total surface: 1.01m²
Pressure withstanding PMT encapsulations for LENA

Pressure simulation results: Hamamatsu R5912 (8”)

Conical encapsulation:
Steel: 1mm thickness, 3.24kg
Acrylic glass: 3mm thickness, 0.50kg
Total surface: 0.53m²

Spherical encapsulation:
Steel: 0.5mm thickness, 4.66kg
Acrylic glass: 4mm thickness, 1.10kg
Total surface: 0.83m²
Pressure withstanding PMT encapsulations for LENA
Pressure simulation results:
Hamamatsu R6594 (5"")

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 withstanding PMT encapsulations for LENA
Pressure simulation results:
Hamamatsu R6594 (5”)

<table>
<thead>
<tr>
<th>Elliptical encapsulation:</th>
<th>Cylindrical encapsulation:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steel</strong>: 2mm thickness, 3.06kg</td>
<td><strong>Steel</strong>: 0.5mm thickness, 2.61kg</td>
</tr>
<tr>
<td><strong>Acrylic glass</strong>: 2mm thickness, 0.22kg</td>
<td><strong>Acrylic glass</strong>: 2mm thickness, 0.22kg</td>
</tr>
<tr>
<td><strong>Total surface</strong>: 0.41m²</td>
<td><strong>Total surface</strong>: 0.46m²</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Height of conical section [mm]</th>
<th>Minimal steel mass [kg]</th>
<th>Minimal acrylic glass mass [kg]</th>
<th>Total surface [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>3.45</td>
<td>0.44</td>
<td>0.535</td>
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<tr>
<td>54</td>
<td>3.20</td>
<td>0.43</td>
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<tr>
<td>70</td>
<td>3.14</td>
<td>0.43</td>
<td>0.535</td>
</tr>
<tr>
<td>130</td>
<td>2.94</td>
<td>0.43</td>
<td>0.549</td>
</tr>
</tbody>
</table>

Conical encapsulation:
Steel: 0.45mm thickness, 2.94kg
Acrylic glass: 2.40mm thickness, 0.43kg
Total surface: 0.55m²
Pressure withstanding PMT encapsulations for LENA

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 withstanding PMT encapsulations for LENA

Pressure simulations: cross-check of results

- Reproducibility
  - Repeated same simulation several times →
    - Same results
  - However only on fast computer - \textit{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)
Pressure withstanding PMT encapsulations for LENA

Next steps:

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

DESIGN + SIMULATIONS

BUILD + TEST PROTOTYPES
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 $\rightarrow$ delay $\approx 0.5-1$ transit time (tt)
      - Ionization / excitation
        - of residual gas molecules near anode $\rightarrow$ delay $\approx 1$tt
        - of molecules/atoms on dynodes (adsorbed/constituents) $\rightarrow$ delay $\approx 0.5-1$tt
      - Partial inelastic scattering of photo electron on first dynode then elastic scattering $\rightarrow$ delay $\approx 0-1$tt
  - SiPM:
    - charge trapping, release time constant $\sim 10-100$ns

Fast Afterpulse in PMT

Fast Afterpulses in SiPM

Development of Silicon Photomultipliers @ IIST, 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 $\rightarrow$ 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 $\approx$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
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 $\rightarrow$ time integral over falling flank gets bigger
  - Problems:
    - Fake main pulses $\rightarrow$ ratio too small
    - Bulgy pulses $\rightarrow$ 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:


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 encapsulation / 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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Attachment to wall