Light Sensor selection for Cherenkov Telescope Array


for the FPI WP of CTA
VHE Ground-Based $\gamma$-ray Astronomy

1. **Galactic Gamma-Ray Sources:**
   - Supernova Remnants
   - Pulsars, Pulsar Wind Nebulae
   - X-Ray Binaries & Micro-quasars
   - Star-Formation Regions
   - The Galactic Centre

2. **Extragalactic Gamma-Ray Sources:**
   - Active Galactic Nuclei
   - Extragalactic Background Light
   - Gamma-Ray Bursts
   - Galaxy Clusters

3. **Fundamental Physics:**
   - Dark Matter
   - Quantum Gravity
   - Charged Cosmic Rays
   - ........ and more

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CTA layout with different telescope sizes

Possible CTA sites
Photosensor requirements:

**Total needs: >1.5 x 10^5 photosensors!**

- Very high Quantum Efficiency
- Almost 100% Collection Efficiency of photo electrons from photo cathode on the 1st dynode
- After-pulsing rate: < 0.02% above 4 Phe (needed to lower the energy threshold)
- Pulse width: < 2 - 3 ns
- Transit Time Spread: ≤ 1.3 ns (single photo electron)
- Stabilize photo cathode to 1st dynode voltage to ~350V
- Linear Dynamic Range > 5000 photo electrons
- About 2 years ago MPI (Max Planck Institute) started a PMT development program with Hamamatsu (Japan) and Electron Tubes Enterprises (England)
Below is shown the wish list of the main parameters of the FPI work package:

**PMT:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. size:</td>
<td>1.5 inch</td>
</tr>
<tr>
<td>2. photo-cathode type:</td>
<td>super-bialkali</td>
</tr>
<tr>
<td>3. sensitivity range:</td>
<td>290 – 600 nm</td>
</tr>
<tr>
<td>4. peak QE on average:</td>
<td>35 %</td>
</tr>
<tr>
<td>5. average QE over Cherenkov spectrum</td>
<td>≥21 % (290-600) (without ph.e. CE)</td>
</tr>
<tr>
<td>6. variation of QE over entrance window</td>
<td>&lt;10 %</td>
</tr>
<tr>
<td>7. 1&lt;sup&gt;st&lt;/sup&gt; dynode ph.e. collection efficiency:</td>
<td>≥95 % (400 nm, 30 mm diameter)</td>
</tr>
<tr>
<td>8. photo cathode to 1&lt;sup&gt;st&lt;/sup&gt; dynode HV:</td>
<td>≥300 V stabilized</td>
</tr>
<tr>
<td>9. 1&lt;sup&gt;st&lt;/sup&gt; dynode gain:</td>
<td>≥ 6</td>
</tr>
<tr>
<td>10. number of dynodes:</td>
<td>8</td>
</tr>
<tr>
<td>11. operating gain:</td>
<td>≥ 4x10&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td>12. afterpulsing for threshold ≥ 4 ph.e.:</td>
<td>≤ 0.02 %</td>
</tr>
<tr>
<td>13. pulse width, FWHM (single ph.e.):</td>
<td>≤ 2.5 ns</td>
</tr>
<tr>
<td>14. transit time spread, single ph.e., rms:</td>
<td>1.0 – 1.3 ns acceptable (30 mm diameter)</td>
</tr>
<tr>
<td>15. single ph.e. peak/valley ratio:</td>
<td>≥ 1.8</td>
</tr>
<tr>
<td>16. protected from geomagnetic field:</td>
<td>µ-metal shield</td>
</tr>
<tr>
<td>17. dynamic range:</td>
<td>≥ 5000 ph.e.</td>
</tr>
<tr>
<td>18. linearity range:</td>
<td>≥ 5000 ph.e.</td>
</tr>
<tr>
<td>19. differential non-linearity</td>
<td>&lt; 1 %</td>
</tr>
</tbody>
</table>
**Evaluation of PMT**

### PMT candidates

<table>
<thead>
<tr>
<th>Company</th>
<th>Type</th>
<th>$\text{QE}_{\text{peak}}(\lambda)$</th>
<th>$&lt;\text{QE}&gt;_{\text{Cher}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu</td>
<td>8619 1&quot;</td>
<td>28.7 ± 2.2 (390 nm)</td>
<td>19.4 ± 0.3</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>9420 1.5&quot;</td>
<td>34.6 ± 3.1 (370 nm)</td>
<td>22.9 ± 0.4</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>7724 2&quot;</td>
<td>38.9 ± 3.3 (370 nm)</td>
<td>25.7 ± 0.4</td>
</tr>
<tr>
<td>Electron Tubes</td>
<td>9117B 1.5&quot;</td>
<td>34.0 ± 3.2 (360 nm)</td>
<td>19.9 ± 0.3</td>
</tr>
<tr>
<td>Electron Tubes</td>
<td>9142B 1,125&quot;</td>
<td>30.2 ± 2.7 (370 nm)</td>
<td>16.5 ± 0.3</td>
</tr>
</tbody>
</table>

Producers claim collection efficiency >90% (direct PDE measurements still needed)

1.5 inch PMTs has been chosen as the target PMT for all 3 types of telescopes.

![Quantum Efficiency curves. Dashed curve: Cherenkov radiation spectrum from 50 GeV $\gamma$-shower.](image)
PMT candidates

Super-bialkali (SBA) 1.5’ PMTs

PMT samples within MPI-Hamamatsu-ET development program:

**Hamamatsu R9420** modified
(convex input window shape)
(mat and polished input window types)

**Hamamatsu R8619** modified
Body of R9420 but used 8619 dynode system (also two window types)

**Electron Tubes 9117B**
After-Pulsing measurements

Requirement for CTA: For the threshold of 4 phe \( P_{AP}(>4\text{phe}) \approx 0.02 \% \) (red line)
After-Pulsing measurements

After-Pulsing sources

Sources vary for different PMTs!

- AP arrival time measurements to distinguish sources
- Peaks: ions from first dynode (H\(^+\), He\(^+\), CH\(_4^+\))
- Plateau caused by rest gases (low plateau = "clean" vacuum)
- ET9142B has very low AP rate with no pronounced peaks

Electron Tubes 9142B

Hamamatsu R9420  
standard and modified

Hamamatsu R8619  
standard and modified
PMT glowing

Dynode system glowing

PMT irradiated by fast laser with various pulse repetition rate:

Hamamatsu R9420MOD
Exposure for every picture: 1 s

4th dynode 2nd dynode

40 MHz 20 MHz 10 MHz 5 MHz 2.5 MHz

direction of incoming photons

laser frequency

CCD counts
Dynode system glowing: Varying of applied voltage

Hamamatsu R9420MOD

100 V
Developed CTA PMT candidate from Hamamatsu

New name: R11920-100-01

R11920

R11920-100-01 (with HA+Mu)

R. Mirzoyan: PMT for CTA Project
These parameters are under improvements

25mm -> 20mm convex window. CE improves, TTS slightly degrades.
First SiPMs candidates

MEPhI - MPI samples:
- Different pitch (50μ, 100μ), p on n type
- Two SiPMs sizes: (1 & 3 mm²)
- Operation voltages 26V and 35V
- In total ~20 different types of SiPMs

Also tested:
- Hamamatsu MPPCs, 1& 3mm, S10362-11-50U
- Planning to test other types when available e.g. Philips, and other manufactures

First prototypes from MEPhI:
1x1mm, 35V and 26V bias voltages.
100μ and 50μ pitch.
No trenches

B, A = different geometrical efficiencies (B-high, A-lower)
Updated SiPMs candidates

Updated MEPhI - MPI (EXCELITAS) samples:

- Type 100A and 100B
- Improved PDE in UV region
- X-Talk suppression: Trenches, second p-n junction, ion implantation...
- Measurements of type A reveal samples with high (and pretty “flat”) PDE:

\[ \text{PDE}(400\text{nm}) \sim 40\% \]

Measurement of PDE for applied over-voltage \((V-V_b)/V_b=15\%\):

Updated prototypes Type 100A \((U_b=37V)\):
Improved UV sensitivity. 1x1mm,
Updated SiPMs candidates

Updated MEPhI - MPI (EXCELITAS) samples:

- Type 100A and 100B
- Improved PDE in UV region
- X-Talk suppression: Trenches, second p-n junction, ion implantation...
- Measurements of type B reveal samples with high (and pretty “flat”) PDE:

  \[ \text{PDE(400nm)} \approx 45\% \]

Measurement of PDE for applied over-voltage \((U-U_b)/U_b=15\%\)

Updated prototypes Type 100B \((U_b=37V)\):
Improved UV sensitivity. 1x1mm,
Updated SiPMs candidates

Updated MEPhI - MPI (EXCELITAS) samples:

- Type 100A and 100B
- Improved PDE in UV region
- X-Talk suppression: Trenches, second p-n junction, ion implantation...
- Measurements of type B reveal samples with high (and pretty “flat”) PDE:

  PDE(400nm)~45% !!!

Measurement of PDE for applied over-voltage \((U-U_b)/U_b=15\%\):

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Updated MEPhI - MPI (EXCELITAS) samples:

- Type 100A and 100B
- Improved PDE in UV region
- X-Talk suppression: Trenches, second p-n junction, ion implantation...
- Cross-talk measurements: Very low crosstalk of

\[ P_{\text{X-talk}}(\Delta U/U_b = 14\%) \approx 5\% \] !!!

Optical cross-talk versus over-voltage \((U-U_b)/U_b\)
(PDE saturates at 10-15% over-voltage)

Updated prototypes Type 100B \((U_b=37V)\):
Improved UV sensitivity. 1x1mm, Optical trenches introduced
Summary

PMTs:

SiPMs:

• One may assume that it could make sense to start using SiPMs in our telescopes once their efficiency will exceed the PDE of PMTs by 1.5-2 times at comparable costs.

• SiPMs are becoming serious sensor candidates for the CTA project: PDE ($\Delta U/U_b=0.15$) $\sim$ 50% reached for low cross-talk $P_{\text{X-talk}}(\Delta U/U_b=0.14) \sim 5%$ !

• Intending to evaluate all new SiPM candidate sensors

• We believe in a few years one can have high quality SiPMs from several manufacturers that can be used also in our project.
Summary

**PMTs:**

- PMT development for the needs of CTA is in progress
- Already now the PMTs of Hamamatsu came rather close to the specified target parameter values: peak PDE ~32%, After-pulsing slightly above 0.02%.
- Next two years further optimization of PMTs from both Hamamatsu and Electron Tubes Enterprises (Some financial support from CTA is foreseen)
- Design and tests of PMT-based pixels and clusters of 7-pixels

**SiPMs:**

- One may assume that it could make sense to start using SiPMs in our telescopes once their efficiency will exceed the PDE of PMTs by 1.5-2 times at comparable costs.
- SiPMs are becoming serious sensor candidates for the CTA project: PDE \((\Delta U/U_b = 0.15) \sim 50\%\) reached for low cross-talk \(P_{\text{X-talk}}(\Delta U/U_b = 0.14) \sim 5\%\)!
- Intending to evaluate all new SiPM candidate sensors
- We believe in a few years one can have high quality SiPMs from several manufacturers that can be used also in our project.