MOLLER Main Detector Simulation & Prototype
- Progress · Status

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Section 1: Detector Simulation
Overview of Detector Simulation

Status at last collaboration meeting:

- Developed a detector simulation package
- Implemented detector array in simulation
- Completed the first iteration of detector design optimization.

Work has been done since then:

- Explored several different design ideas
- Studied the effects of using pre-radiator
- Integrated detector array in full MOLLER simulation environment
- Investigated background/interference issue
- Performed the geometry optimization
Recall: single detector model and simulation result at last collaboration meeting

- Single detector model: this model was selected for its simple geometry, small edge effects and high #PE yield

- Quartz radiator: 1.5 cm thick, two 45 deg cuts at bottom

- PMT: 3 inch, round, head-on, quartz window, with a radial location of 120 cm (from beam axis to photocathode)

- Reflector: 3.5 cm long, 19 deg opening angle

- Light guide length: 120 cm – radial location of the outer radius edge of quartz radiator (e.g. 15 cm for e-e ring detectors)

- Light guide reflectivity: assuming 93%, uniform over full spectrum and all incident angles

- #PE yield: ~ 30 for detectors on e-e ring, with an excess noise of ~ 3%
## Exploring Several Design Ideas

<table>
<thead>
<tr>
<th></th>
<th>pros</th>
<th>cons</th>
<th>option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winston cone light guide</td>
<td>A little bit more #PE (&lt; 5%) in e-e tail ring</td>
<td>complicated geometry</td>
<td>No</td>
</tr>
<tr>
<td>Squar window PMT</td>
<td>Matching light guide shape, large acceptance area, increasing #PE yield of 10-15%</td>
<td>Not popular</td>
<td>Yes or no, depending on cost if custom build is required</td>
</tr>
<tr>
<td>Vacuum core light guide (rough vacuum 100 – 1000 Pa)</td>
<td>Effectively reducing the background lights arising in light guide due to Cerenkov radiation in air</td>
<td>Engineering difficulties and higher cost</td>
<td>No</td>
</tr>
<tr>
<td>Pre-radiator</td>
<td>Blocking soft background, greatly increasing #PE</td>
<td>Shower background, large RMS width</td>
<td>Backup</td>
</tr>
</tbody>
</table>
Example: Pre-radiator

- An optional/backup design, to deal with the possibly large soft background.
- Higher #PE yield, but worse detector resolution
- Background due to shower in pre-radiator itself could be an issue.

Optimized pre-rad thickness: 4 – 5 radiation length
Implementation of Detector Rings in MOLLER Simulation Environment

- Beam focusing on detector rings with different Z was studied
- #PE yields in full simulation environment agree with the results in the independent detector simulation
- Background/interference issue was investigated

Implementation of detector ring in main Moller simulation

(https://jlabsvn.jlab.org/svnroot/moller12gev/mollersim/branches/peiqing_mollersim_gdml/ )
Background/Crosstalk/Interference

1. Background/crosstalk/Interference complicate our interpretation of data

2. increase rms, and in turn the beam time to reach the required statistics

3. Example sources (a coarse classification):

   A: events hitting quartz detector (will not be discussed):
   - events originated from target windows, vacuum chamber windows, etc.
   - elastic e-p and inelastic e-p events which hit the e-e detectors
   - upstream shower events (e-/e+, gamma) from beamline, collimator, magnet etc.
   - shower events from surrounding materials, such as quartz, light guides, shielding, etc
   - any other room background, cosmics, low energy gamma, after-glow due to activation etc.

   B: events hitting light guide:
   Any events which hit light guide, and then generate effective photoelectrons in PMT

   C: events hitting PMT:
   Any events which hit PMT, and then generate effective photoelectrons in PMT
Type B&C Contributions

A typical background spectrum

( the PMT spectrum after cutting off events which hit the corresponding quartz )

Interference events (e+, e-, gamma, etc) cut off these events which hit the quartz

Type B events mostly contribute to low-end tail

Type C events mostly contribute to high-end tail

Three methods were used to verify and characterize these two types of background:

- checking the optical photon position and direction at the origin of generation
- changing the radial position of PMT to see if we can reduce the high-end tail
- changing the vacuum level of the air in light guide to see if we can reduce the low-end tail
Study Background Under Different Configurations

**Config. 1:**
using e-e generator, PMT window radial location $R = 120$ cm, standard air (0 degree, 1 atm) with refractive index $n = 1.00029$.

**Config. 2:**
Based on config. 1, but $R = 140$ cm
*
\textit{i.e. radial location of PMT was increased 20 cm}.

**Config. 3:**
Based on config. 2, but putting the light guide in a pure vacuum (the refractive index of air $n = 1.0$)
*
\textit{i.e, pure vacuum, Cerenkov in air was totally turned off}

**Config. 4:**
Based on config. 2, but putting the light guide in a rough vacuum (20 degree, 1000 Pa), refractive index varying with photon wavelength and $n < 1.0000027$.
*
\textit{i.e, effects of Cerenkov in air was reduced (not totally off)
Cerenkov Light Yield in Air

Reasoning for config. 3 & 4:
- to see if vacuum can effectively reduce the low-end tail,
- in turn to confirm the source of the low-end tail

From Frank-Tamm equation, Cerenkov light yield is approximately proportional to $n$ when $n$ is close to 1;

$dN/dE/dx = 0.22 /$eV/cm,
No Cerenkov light at $n=1$.

Refractive index of air is approximately proportional to air pressure under vacuum condition.

Normal condition (1 atm):
$n=1.0003$
Pure vacuum: $n=1$.

Cerenkov light yield is proportional to air pressure under vacuum condition.

At rough vacuum level: $P=1000 \text{ Pa}$, $n=1.000003$, $dN/dE/dx = 0.0022 \text{ /eV/cm}$

- We could also quantitatively understand how much the Cerenkov lights in air contribute to background.
Analysis Sample

- There are 84 detectors on e-e ring
- These detectors have sequenced ID numbers (#112 - #195) in the simulation
- We took Det#112 & Det#118 at as an example
- Det#112: located at high rate region
  Det#118: located at low rate region
Config. 1-3: Spectrum of Detector #112 & #118

Config. 1
Total #PE (signal+bkg) Spectrum for Det#112 - Det#112
- Entries: 4400
- Mean: 44.98
- RMS: 23.67

- Entries: 3730
- Mean: 51.48
- RMS: 12.56

- Entries: 862
- Mean: 16.63
- RMS: 36.12

Config. 2
Total #PE (signal+bkg) Spectrum for Det#112 - Det#112
- Entries: 5121
- Mean: 32.33
- RMS: 12.04

- Entries: 5567
- Mean: 34.91
- RMS: 10.1

- Entries: 914
- Mean: 12.15
- RMS: 17.1

Config. 3
Total #PE (signal+bkg) Spectrum for Det#112 - Det#112
- Entries: 4072
- Mean: 33.76
- RMS: 11.01

- Entries: 437
- Mean: 5.906
- RMS: 11.68

- Entries: 3961
- Mean: 34.46
- RMS: 10.06

Location of det#112
Location of det#118
### Results Comparison for All Detectors on e-e Ring

<table>
<thead>
<tr>
<th>Configuration 1: R=120 cm, air (P=1 atm, t=0 °C, ( n_{\text{air}} = 1.00029 ))</th>
<th>Configuration 2: R=140 cm, air (P=1 atm, t=0 °C, ( n_{\text{air}} = 1.00029 ))</th>
<th>Configuration 3: R=140 cm, vacuum, (P=1 atm, t=0 °C, ( n_{\text{air}} = 1.0 ), no Cerenkov in Air)</th>
<th>Configuration 4: R=140 cm, rough vacuum (P=1000 Pa, t=20 °C, ( n_{\text{air}} &lt; 1.000003 ), tiny Cerenkov effects in Air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate ratio (bkg:signal:total)</td>
<td>1 : 2.3 : 3.3</td>
<td>1 : 5.5 : 6.5</td>
<td>1 : 11.3 : 12.4</td>
</tr>
<tr>
<td>Total #PE</td>
<td>35.9 +/- 25.7(RMS)</td>
<td>29.8 +/- 14.3(RMS)</td>
<td>31.2 +/- 13.2(RMS)</td>
</tr>
<tr>
<td>Signal #PE</td>
<td>49.2 +/- 13.5(RMS)</td>
<td>33.8 +/- 9.8(RMS)</td>
<td>33.7 +/- 10.0(RMS)</td>
</tr>
<tr>
<td>Bkg #PE</td>
<td>6.0 +/- 21.0(RMS)</td>
<td>8.2 +/- 15.5(RMS)</td>
<td>3.9 +/- 12.1(RMS)</td>
</tr>
<tr>
<td>Bkg/total charge</td>
<td>5.2%</td>
<td>4.2%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Signal/total charge</td>
<td>94.8%</td>
<td>95.8%</td>
<td>99.2%</td>
</tr>
<tr>
<td>S/B (signal-to-bkg ratio)</td>
<td>18.4</td>
<td>22.6</td>
<td>126</td>
</tr>
<tr>
<td>Det. Resolution</td>
<td>0.714</td>
<td>0.479</td>
<td>0.423</td>
</tr>
<tr>
<td>Summary</td>
<td>big tails at both low-end and high-end</td>
<td>high-end tail was removed, but #PE shrunk a lot.</td>
<td>low-end tail was largely reduced</td>
</tr>
</tbody>
</table>

**Note:**
- The tabled values are averages over all 84 detectors of e-e ring.
- These results were obtained with Moller (e-e) event generator only. The S/B will be much worse if all types of events, such as e-p elastics, inelastics, were simultaneously simulated as well.
- The scintillation yield in air varying with air pressure/density has not been implemented in this simulation.
- The residual backgrounds are scintillation, as well as crosstalk due to leakage of light guide opening at quartz side.
Summary of Background Studies

• Major sources of the tails on #PE spectra:
  - Low-end tail: Cerenkov light in air-core light guide
  - High-end tail: Cerenkov in PMT window due to direct hit

• Low-end tail of the spectrum could be much bigger if events from other generators (e-p elastic, inelastic etc.) were also taken into account

• Methods for reducing tails:
  - High-end tail: increasing light-guide length (with side effects of less #PE), better shielding (especially, shield the beam and shower events from upstream)
  - Low-end tail: making vacuum in the light guide or changing geometry.

Note: the idea of making rough vacuum in the light guide was abandoned after a group discussion with KK et. al. It was proposed to study “geometry optimization” to reduce the low-end tail.
Alternative Detector Model

**Bottom wedge cut:**

- Allowing the Cerenkov light to escape easily from quartz with specific direction, and to reduce the loss due to bouncing in quartz

**Tilting light guide towards beam:**

- Matching the angle of escaping Cerenkov light from quartz (**green**), so as to minimize the loss due to bouncing on light guide inner surface

- Directing the Cerenkov light in air (**blue**) to the opposite side of PMT, so that these interferences can be reduced by bouncing in light guide
**Spectrum of Detected Photons**

**Detection efficiency** of optical photons is mainly affected by the reflectivity of light guide material and the quantum efficiency of PMT.

The number of Cerenkov photons emitted per cm is

$$\frac{dN}{d\lambda} = \frac{2\pi z^2 \alpha}{\lambda^2} \left(1 - \frac{1}{\beta^2 n(\lambda)^2}\right)$$

Cerenkov photons are mostly generated in deep UV.
Optimization of Acceptance Angle

Acceptance angle: the angle between light guide and quartz

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Refractive index n</th>
<th>Cerenkov angle $\Theta_C$ [degree]</th>
<th>$\Theta_{in}$ [degree]</th>
<th>$\Theta_{out}$ [degree]</th>
<th>Acceptance angle $\Theta_A$ [degree]</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>1.575</td>
<td>50.6</td>
<td>5.6</td>
<td>8.3</td>
<td>36.7</td>
</tr>
<tr>
<td>250</td>
<td>1.507</td>
<td>48.4</td>
<td>3.4</td>
<td>5.2</td>
<td>39.8</td>
</tr>
<tr>
<td>300</td>
<td>1.485</td>
<td>47.7</td>
<td>2.7</td>
<td>4.0</td>
<td>41.0</td>
</tr>
<tr>
<td>700</td>
<td>1.455</td>
<td>46.5</td>
<td>1.5</td>
<td>2.4</td>
<td>42.6</td>
</tr>
</tbody>
</table>

Best acceptance angle:

From simulation, #PE yield is maximized at an acceptance angle of $\sim$41 deg, with a small tolerance ($\sim$1 deg).

Reasoning:

Optical photons at peak wavelength (300 nm) have the minimized number of bounces on the light guide surface.
Light Propagation without Light Guide

A bare quartz in simulation, to observe the Cerenkov photon propagation (without light guide).

TIR preserved inside quartz

electron

Cerenkov photons exit from the bottom wedge

with ~41 deg central angle

Destroy TIR to extract photons out
In order to maximize #pe yield:

- Keep acceptance angle (41 deg) unchanged
- Tilt quartz so that quartz tilt angle = scattered beam angle

- Tilting quartz properly could reduce the #PE loss of ~ 10 – 20%
- It is worth the effort to put more strict precision requirement on detector construction and installation.
Implementation

Implemented in the independent detector simulation package:

Configuration:

- Quartz thickness: 1.5 cm
- Quartz tilt angle: 4 deg
- Light guide acceptance angle: 41 deg
- Length of e-e ring light guide: 34 cm
- Light guide material: Anolux-UVS
- PMT: 3” round quartz window

#PE yield of e-e ring detector:

- ~37 PE
- rms: 8.7

To see the background/interference, an implementation in the full MOLLER simulation environment is underway.
Section 2: Detector Prototype
Prototypes for Beam Test

For beam test, we would like to construct prototypes based on 3 models:

Configurations:

- Varying beam incident position/angle on quartz and light guide
- Varying quartz and light guide tilt angles
- Switching light guide materials
Light Guide Material

• Light guide material should have excellent reflectivity in UV.

• Polished aluminium has super good reflectivity in deep UV.

• Concern: possible damage to interior finish of light guide due to: NOx + humidity + oxidation, etc.

• Polished Al needs dielectric protection coating, which usually degrade the reflectivity in deep UV.

• In addition, commercial products (low cost) are preferable.

Contact with ALANOD Aluminium- Veredlung GmbH & Co. KG (the major vendor):

Anolux-UVS could be a suitable choice.
Anolux-UVS from Anomet

Simulation Study:
- Implemented the spectrum in detector simulation
- OK if the actual products have the claimed responses

Actual reflectivity will be measured!

Average reflectivity at our band of interests (250 nm – 700 nm): ~83%
# Prototyping Preparation

## Material & Component:

<table>
<thead>
<tr>
<th></th>
<th>Required</th>
<th>On-hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>18 cm x 8 cm x 1.5 cm (optical grade polish)</td>
<td>8 cm x 6 cm x 2.5 cm (need cut and polish)</td>
</tr>
<tr>
<td>PMT</td>
<td>3” quartz window</td>
<td>Hamamatsu H1949-51, 2” Borosilicate glass window (available soon: Photonics XP2268, 2” quartz window)</td>
</tr>
<tr>
<td>Light guide</td>
<td>Anolux-UVS (~80% in UV 250 – 400 nm)</td>
<td>Alazk Miro-4 (cut-off at 380 nm) &amp; Anolux-UVS</td>
</tr>
</tbody>
</table>

## Variation:

- Using on-hand materials and components to build the prototypes (Hard to cut the 2.5 cm thick quartz to 1.5 cm thin, No 3” PMT available)
- Benchmark simulation against this variation is in progress
Raw Quartz Blocks

- Obtained 4 quartz blocks (Qweak’s leftover samples, thanks to Dave Mack)
  - Size: 120 x 60 x 25 mm³ (3 pieces)
  - Size: 80 x 60 x 25 mm³ (1 piece)
  - Required size for MOLLER prototype: 180 x 84 mm x 15 mm³

- Cutting and optical grade polishing are primary cost factors
- Too many difficulties to make it thinner
- Try cross cut and angle cut only
Quartz Radiators

- On-hand quartz blocks can only be cut to the shapes indicated by the green shades.
- OK to use shorter quartz for test purpose since length is not a dominated factor of light yield for such a small detector if the surface polishing is good.
Cutting Tools: Diamond Saw

- Quartz is one of the hardest materials
- Rough cut can be done with usual wet tile saw (cuting loss > 2 mm)
- Angle cut should be done with precision diamond saw (cuting loss ~ 0.5 mm)
Quartz Cutting

- Using precision diamond saw (ISOMET 1000)
- Jigs were made for angle and cross cuts
- Cutting loss due to blade thickness: < 1 mm
- Extended cutting time to avoid chipping
Quartz Radiator Samples After Cut

- 3 quartz samples were cut to desired shapes
- Polishing is in progress
First Detector Prototype

- The 1st detector prototype was constructed using Alazk light guide
- Construction of light guide using UVS sheet is underway
DAQ & Cosmic Test Setup at U. of Manitoba

- Dark box: containing the trigger scintillators & the prototype detector
- Amplifier, Discriminator, Logic Unit, Charge ADC & Flash ADC
- HV power supply

- Software: TRIUMF MIDAS framework, online(realtime) & offline analysis
- Able to do charge integration analysis and single event waveform analysis
## “Preliminary” Test

<table>
<thead>
<tr>
<th>Current Test Configuration</th>
<th>“Future” Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpolished raw quartz block</td>
<td>Polished quartz with wedge cut</td>
</tr>
<tr>
<td>Alazk light guide</td>
<td>Anolux-UVS light guide</td>
</tr>
<tr>
<td>Non-quartz window 2” PMT</td>
<td>Quartz window 2” or 3” PMT</td>
</tr>
</tbody>
</table>

- Basic functionality test for cosmic ray test stand, DAQ etc.
- \( \sim 5 – 8 \) PE (very preliminary, not carefully calibrated)
- Low #PE and broden distribution due to “non-ideal” configuration, but the signals could be clearly seen.
- Real prototype cosmic ray tests will be started SOON when the quartz polishing are completed

![Graph](https://via.placeholder.com/150)

**Counts**

<table>
<thead>
<tr>
<th>Channel number of charge integration ADC</th>
</tr>
</thead>
</table>
Add-on: Double-Shutter for Bkg Measurement

- Would like to have a double-shutter for each detector
- One shutter is at PMT side (shutter A), another is at quartz side (shutter B)
- Allowing us to measure background in light guide during experiment

Normal operation  
Background in light guide & PMT  
Background in PMT (dark noise)

Concept of Double-shutter System
Add-on: Diagnostic/Calibration LEDs

- Would also like to have diagnostic/calibration LEDs in light guide
- Two LEDs are mounted on side wall of light guide. To avoid radiation damage, they should be mounted near PMT.
- Operating in continuous mode or pulse mode
- Useful in checking electronics chain, measuring linearity and gain, calibrating SPE, and so on.
Summary

**Simulation:**
- Work done: single detector study, detector rings in full MOLLER simulation environment, background/interference study, optimization of detector geometry.
- Basic design (1.5 cm thick quartz, 3” PMT, air-core light guide) meets our requirements, but with potential issue of background/interference.
- Full simulation in MOLLER simulation environment with different models is underway to quantitatively understand the Bkg-to-signal ratio, and to evaluate the effects etc.

**Prototyping:**
- 3 detector models were selected for beam test
- A variation of required materials and components is obtained.
- Quartz radiators were cut and the first prototype is completed
- Cosmic ray test stand is set up and fully functioning.
- We are in rapid progress on the construction of several prototypes for the cosmic ray test and upcoming beam test.