Geant4 simulation of the DIRC-like forward TOF detector

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Outlook

\begin{itemize}
\item Master formulae for time resolution
\item From fDIRC to fTOF simulation
\item Geant4 simulation
\item Electronic readout simulation
\item Studying Chromatic, Transit Production and Photon Track contributions to the timing error
\item Conclusions
\item Work with Kiev Taras Shevchenko University, Collaborative tools
\end{itemize}

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Master formula 1 for time resolution

Two particles hypothesis with masses $m_1$, $m_2$, with same momentum $p$ flying over a distance $L$, have a $\Delta t$ time flight difference given by:

$$\Delta t = \frac{Lc}{2p^2} \left( m_1^2 - m_2^2 \right)$$

Main requirements:

- 20 – 25 ps time resolution enough to make 3 - 4 'sigma' K/pi separation @ 3GeV with $L = 2$ m

To avoid degrading significantly the EMC resolution, any fPID detector should have a small radiation length.
Master formula 2 for time resolution

The \((\text{time}_{\text{measured}} - \text{time}_{\text{expected}})/\text{error}\) ratios (one for each particle hypothesis) define likelihood values which are then used to construct LH-based PID selectors.

The accuracy of the \(\text{time}_{\text{expected}}\) term is related to the precision with which flight length and momentum are measured. These can be studied with FastSim.

\[
\text{Time}_{\text{measured}} = \text{Time}_{\text{stop}} - \text{Time}_{\text{start}}
\]

Precision on the \(\text{Time}_{\text{start}}\) dominated by time of the bunch crossing \(\sigma_{T0} \approx 15\text{ps}\).

In the following we study \(\text{time}_{\text{stop}}\) which is given by the TOF detector.
Master formula 2 for time resolution

\[ \sigma_{\text{stop}} = \sqrt{\left(\frac{\sigma_{\text{Electronics}}}{N_{\text{channel}}}\right)^2 + \left(\frac{\sigma_{\text{Chromatic}}}{N_{\text{pe}}}\right)^2 + \left(\frac{\sigma_{\text{TTS}}}{N_{\text{pe}}}\right)^2 + \left(\frac{\sigma_{\text{TransitProduction}}}{N_{\text{pe}}}\right)^2 + \left(\frac{\sigma_{\text{PhotonTrack}}}{N_{\text{pe}}}\right)^2} \]

- \( N_{\text{channel}} = 16 \) readout channels
- \( N_{\text{pe}} \) Number of photo electrons
- \( \sigma_{\text{PhotonTrack}} \) (for \( \lambda = 450\,\text{nm} \)) = 90 ps
- Timing spread due to different photon path length.
- Kaon hit in center of the barrel
- \( \sigma_{\text{TransitProduction}} = 11.7\,\text{ps} \)
- Cerenkov light produced all along the way in the quartz detector.
- For instance, for K @ 3 GeV the transit time at 1.2cm thick detector is 40.6 ps.
From simulation of the fDIRC to simulation of the DIRC-like fTOF

Starting point: the standalone Geant4 simulation of the focusing DIRC.

Material properties, physical and boundary processes are same for focusing DIRC and forward TOF. Only geometry has to be changed.
Simulation of the Cerenkov effect in Geant4

0.5GeV kaon in quartz

Cerenkov photons emitted all along the way particle cross detector

\[ \sin(\theta_1) = \frac{n_2}{n_1} \quad \sin(\theta_2) = \frac{n_1}{n_1} \]

Photons from kaon with momentum 1GeV will leave detector. By putting mirrors we can avoid this effect

Spectrum of the emitted photons goes like \( 1/\text{(Lambda}^2) \)

Cerenkov photons emitted all along the way particle cross detector

3GeV kaon hit detector at 90° to the surface with random x and y.

Wavelength distribution, [0]/x^2 + [1]

| h1WL |  
| --- | --- |
| Entries | 612037 |
| Mean | 430.1 |
| RMS | 96.99 |
| \( \chi^2 / \text{ndf} \) | 0.007474 / 28 |
| p0 | 8.085e+05 ± 173162 |
| p1 | -0.0655 ± 0.8049 |

\[ \cos(\theta_{Cerenkov}) = \frac{1}{n(\lambda) \beta \theta} \]

\[ \beta_{ct} \]

P

n1

\( \theta_1 \)

v1

n2 index

\( \theta_2 \)

\( v_2 \) velocity

normal

interface

Q

O

Photon's path through quartz with Cerenkov effect.
Simulation of the optical properties of the quartz

Effects which could reduce the photon rate

Absorption in quartz bar

Free path length is in km in this plot

This effect is negligible small, Characteristic photon path length is around 50cm in fTOF.

Each time photon deflect from boundary non zero probability to hit dust exist.

Less than 5% of the photons lost after 20 reflexions regardless of their wavelength.
Simulation of the optical properties of the quartz

Speed of propagation of the photons in quartz is the function of their wavelength !!!!

Time spread due to this known as Chromatic effect

\[
\cos(\theta_{Cerenkov}) = \frac{1}{n(\lambda) \beta}
\]

\[
\chi^2/\text{ndf} = 1.103e-07 / 31
\]

\[
p0 = 1.758 \pm 0.005836
\]

\[
p1 = -0.001916 \pm 5.201e-05
\]

\[
p2 = 4.863e-06 \pm 1.703e-07
\]

\[
p3 = -5.708e-09 \pm 2.432e-10
\]

\[
p4 = 2.559e-12 \pm 1.278e-13
\]

Different in arriving time between blue and red (650nm) lights, for different photon path length.
Detector is trapezoid, with size:

- \( L \) – length 30 cm
- \( X_{\text{min}} \) – length 25.9 cm
- \( X_{\text{max}} \) – length 41.4 cm

Thickness – 12.0 mm

4 MCP – PMTs

A simple geometry simulated so far; next step will be to compare different ones.
Simulation of the different photocathodes

Integral QE = 100% 44
Bialkali 6
GaAsP 12
GaAs 4
Width = 1.2 cm

3GeV kaon hit detector at 90° to surface with randomly generated x and y.
Convolution between chromatic and transit production terms

time for 249.7mm < photon path length < 250.3mm

To study chromatic transit production and photon track terms, simulation of the TTS and electronics is not needed.
RMS of the time vs photon path length profile

$RMS = \sqrt{\sigma_{Chromatic}^2 + \sigma_{TransitProduction}^2}$

Constant pedestal correspond to
Sigma$_{TransitProduction}$ = 40.6 ps/sqrt(12) = 11.7 ps

Chromatic term can be evaluated

$\sigma_{Chromatic} = \sqrt{(RMS^2 - \sigma_{TransitProduction}^2)}$
Convolution between the Transit Production and Photon Track terms

\[ \sigma = \sqrt{\sigma_{\text{TransProd}}^2 + \sigma_{\text{PhotonTrack}}^2} \text{ nS} \]

\[ \sigma = (-1.02 \times 10^{-5}) \lambda + 0.1 \]

\[ \sigma_{\text{PhotonTrack}}(450\text{nm}) = 90\text{ps} \]

We can correct it

“blue” photons have more spread path length
The design currently studied has, effective surface $2.2 \times 4 \text{ mm} = 8.8 \text{ cm}$ (34 % from total)

Position resolution is about size of the channel $\sim 5.5 \text{ mm}$

Different geometries of connectors between quartz bar and PMTs have to be studied

Connectors with a more complicated geometry would allow the effective surface to be increased.

How PMTs should be placed?
Simulation of the time spread due to TTS and electronics

Time of each photoelectron smeared by TTS = 35ps

Each channel has its own 10ps time spread, which affect all photoelectrons in same channel.

In general we have only one photon per channel, but if two photons enter same channel the actual measurement is a time average.

Taking into account measurements from all channels and their weight (number of photons) the average time $t_{average}$ is evaluated.

Next slide shows a study of the time $t_{average}$ RMS
Studying RMS of the time average for Kaon at 3GeV which hit in the center of the detector perpendicular to the surface.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Mean</th>
<th>RMS</th>
<th>Entries</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bialkali</td>
<td>1.21</td>
<td>0.04768</td>
<td>997</td>
<td>47ps</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.192</td>
<td>0.05957</td>
<td>982</td>
<td>59ps</td>
</tr>
<tr>
<td>GaAsP</td>
<td>1.199</td>
<td>0.03577</td>
<td>1000</td>
<td>36ps</td>
</tr>
<tr>
<td>Qe=100%</td>
<td>1.207</td>
<td>0.02455</td>
<td>1000</td>
<td>25ps</td>
</tr>
</tbody>
</table>

All times are in ns.
Numbers of photons studying for Kaon at 3GeV which hit in the center of the detector perpendicular to the surface.

Number of photons is very important parameter. How can we increased it?

By increasing thickness of the detector
By increasing number of readout channels
By changing geometry of the connector between quartz bar and PMTs
We can correct $\sigma_{\text{PhotonTrack}}$.

No TTS speared
No electronics spread

$\sigma_{\text{PhotonTrack}}(450) = 90\text{ps}$

Correction

$\sigma_{\text{PhotonTrack}}(450\text{ns}) = ?$

This job has to be done
Conclusion

For kindly providing the G4 package after the SLAC workshop
Many thanks to Doug Roberts

➤ Geant4 simulation of the fTOF detector study started
➤ Study the effect of the Chromatic, Transit Production and Photon Track terms
➤ Studying effect of different photocathodes on time resolution
➤ Collaborative work with Kiev Taras Shevchenko University, Ukraine

To do list

➤ Add connectors between quartz bar (TOF) and PMTs in to the simulation
  ➤ Study different geometries
➤ Study effect from different thickness
➤ More realistic simulation of the electronics have to be done
➤ Study of different geometries of the detector in general
Collaborative tools

We started to collaborate with Kiev Taras Shevchenko University

Dedicated please for simulation of the fTOF

https://ftof.bezsh.org.ua/

login: guest   password: welcome

WELCOME to fTOF subproject page

This is a small part of HEP project SuperB ➔ http://web.infn.it/superb/ (old web server - ➔ http://www.pi.infn.it/SuperB/)
Some more information can be found here: ➔ http://www.slac.stanford.edu/~burmist/TOFinfo/
Backup
Convoluted between Chromatic and Transit Production terms

\[ \sigma_{\text{res}} = \sqrt{\left( \sigma_{\text{TransitProduction}}^2 + \sigma_{\text{Chromatic}}^2 \right)} \]

RMS of the time vs photon path length profile

Constant pedestal ~ 11.7 ps correspond to photon produced all over the way

What we see on this plot is convolution between \( \text{Sig}_{\text{TransitProduction}} \) and \( \text{Sig}_{\text{Chromatic}} \).
Extraction of the Chromatic term

Chromatic term can be evaluated like this

$$\sigma_{\text{Chromatic}} = \sqrt{\sigma_{\text{res}}^2 - \sigma_{\text{TransitProduction}}^2}$$

GaAs has the smaller error from chromatic term since it selects more “red” photons.
To get the code from svn and run simple example

Programs which you need to install fTOF
   1) svn
   2) Geant4 (geant4.9.2.p02)
   3) root
   4) Java (for visualization with HepRep)

1) Load the code > svn -u username user https://www.bezsh.org.ua/svn/fTOF/trunk
2) make
3) run executable with vis.mac files (Geant0.heprep and Geant1.heprep should appear)
Gain Dependence on B-Field Direction, define how PMT have to be connected to the quartz bar

\[ \phi = \text{angle between magnetic field direction and PMT-axis} \]

Hamamatsu SL10 (10 \( \mu \)m)

**Gain Dependence on Tilt Angle** \( \phi \)

- PMT should work with gain \( 10^6 \)
- \( \phi \) have to be 0 deg

\[ B = 1.5 \, \text{T} \]

Significant gain drop at large magn. fields and \( \phi \)-angles

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Results we get for now

<table>
<thead>
<tr>
<th>h1Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>

Sig\_electronics = 10ps

Sig\_T0 = 15ps

Sig\_TTS = 35ps

photocathode - GaAsP

thickness = 20.0mm

The RMS and mean was extracted from histogram with no FIT

Sig\_electronics – effect all photons (should effect just one channel)
Geometry of fTOF in Geant4

For the moment just this geometry was studying

Detector is trapezoid, with size:
- \(Y\) – length 30 cm
- \(X_{\text{min}}\) – length 25.9 cm
- \(X_{\text{max}}\) – length 41.4 cm
- Thickness – 12.0 mm

Sizes with some changes taken from this presentation of J. Vavra