Challenges to design compact gaseous RICH with $\pi/K$ PID at 50 GeV/c

J. Va'vra, SLAC, retired

Discussions with: A. Schartzman, V. Cairo, M. Basso, Ch. Damerell, Su Dong

Motivation for this work can be found in:

Can we achieve $\pi/K$ PID at 50 GeV/c?

Goal of my talk is to convince you that it is possible.

RICH in this talk
Our RICH design concept is derived from CRID/Delphi RICH

**SLD CRID:**

- Gas Radiator: (C₅F₁₂/N₂ Mix)
- Mirror Array
- Drift Box
- Detector
- Liquid Radiator: (C₈F₁₄)
- C₂H₆ + TMAE

**Delphi RICH:**

- Gas Radiator
- Midplane
- Drift Box
- Mirror Array

**Our proposed RICH:**

- **C₄F₁₀ at 1 bar (boiling point -1.9°C at 1 bar)**
- Beryllium mirrors with reflective coating
- Low mass carbon-composite structure
- Timing will be used to cut SiPM noise
- SiPM detector will run at +2-3°C
To help Mathematica with mirror parameters choices, it is necessary to do ray tracing first.

- Spherical mirrors have radius \( R = 50 \text{ cm} \), focal length \( f = 25 \text{ cm} \) nominally, except mirrors at large \( \theta_{\text{dip}} \).
Although CRID operated in a region where refraction index changed more rapidly, its wavelength acceptance was very narrow and therefore the chromatic error was smaller: $\sigma_{\theta,\text{single photon}} \sim 0.4 \text{ mrad (TMAE) vs. } \sim 0.62 \text{ mrad (SiPM)}$.

- FBK SiPM QE enhances lower wavelengths.
Npe and $\theta_c$ in our present design for FBK SiPM

$$N_o = \left(\frac{\alpha}{hc}\right) \int Eff(E)[\sin(\theta_c)]^2 dE$$

$$N_{pe} = N_o L [\sin <\theta_c>]^2 = 260 \text{ for FBK SiPM}$$

$$\cos \theta_c = 1/(< n > \beta)$$

$< \theta_c>$ is mean Cherenkov angle

$\bullet$ $L = 25 \text{ cm} \& 1 \text{ bar.}$

---

**SiPMT**

---
Created tracking program in Mathematica

Follow helix step by step. In each step:

\[ x(i+1) = x(i) - R(\cos(\omega(i) + s \cos \theta_{EL}/R) - \cos(\omega(i))) \]
\[ y(i+1) = y(i) + R(\sin(\omega(i) + s \cos \theta_{EL}/R) - \sin(\omega(i))) \]
\[ z(i+1) = z(i) + \sin \theta_{EL} \]
\[ s \cos \theta_{EL} = [z(i+1) - z(i)] P_{y'}/P_{L} \]

- Time \( t_0 \) could be a special timing layer (\( \sigma_{\text{start}} = 10 \text{ps} \)), \( t_1 \) is FBK SiPM time (\( \sigma_{\text{stop}} = 25 \text{ps} \)).

Details in appendix
Time information for $\theta_{\text{dip}} = 4^\circ$ & 20 GeV/c & $B = 5$ Tesla

(Pions)

Cut on “$t_1-t_0$” time will be used to reduce SiPM noise

$\sigma_{\text{start}} = 10$ ps
$\sigma_{\text{stop}} = 25$ ps

$t_1-t_0 = \text{Total time} = \text{Track time} + \text{Photon time 1} + \text{Photon time 2 (psec)}$
Smearing and focusing errors - which one dominates?

- Both effects make rings slightly fuzzy at certain Cherenkov angle azimuths $\phi_c$.
- The focusing error is larger than the smearing error for $p > 20\text{GeV}/c$ – see appendix.
Illustration of ring distortions at $\theta_{\text{dip}} = 4^\circ$ & 20 GeV/c & B = 5 Tesla

- I rotated detector plane arbitrarily. Images are ellipses with fuzzy edges.
Cherenkov rings for $\theta_{\text{dip}} = 4^\circ$ & 20 GeV/c & $B = 5$ Tesla
(Nominal geometry)

Based on one event, one does not recognize any distortion. However, it is clear in a sample of 300 tracks. The final image is an ellipse.

Data have no corrections. Fit a circle to raw hits without any initial guess. Fit determines $x_0$, $y_0$ and radius.

- Based on one event, one does not recognize any distortion. However, it is clear in a sample of 300 tracks. The final image is an ellipse.
Correction for ellipse distortion at $\theta_{dip} = 4^\circ$ at 50 GeV/c with $B = 5$ Tesla (Nominal geometry)

- This fit is used to correct raw Cherenkov angle.

**Raw ring radius:** $\text{CherRadius} = \sqrt{(z_{\text{final}[i]} - z_0)^2 + (x_{\text{final}[i]} - x_0)^2}$ ($x_0$, $z_0$ - see previous page).

**Raw Cherenkov angle:** $\theta_c\text{-raw} = \text{CherRadius}/(\text{Focallength})$; (have to supply $x_0$, $z_0$, Focallength)
Results of the correction for $\theta_{dip} = 4^\circ$ & $B = 5$ Tesla
(Focusing/smearing errors only)

Typical rms error = 0.25 mrad per single hit (includes tails)

$\Delta \theta_c = \theta_c(\text{pion}) - \theta_c(\text{Kaon}) = 0.85$ mrad

- **Cherenkov angle distribution dramatically improves after the correction for ring distortion. At this point we consider focusing & smearing error only.**

![Graphs showing corrected Cherenkov angle distributions for Kaons and Pions at 20 GeV/c, 30 GeV/c, and 50 GeV/c.](image)
PID for $\theta_{\text{dip}} = 4^\circ$ & 20 GeV/c

- Do not see much difference in the corrected Cherenkov angle distribution.

- rms error = 0.254 mrad per single hit

2 Tesla

5 Tesla

Corrected Cherenkov angle for Kaons and pions (mrad)
Cherenkov rings for $\theta_{\text{dip}} = 40^\circ$ & 50 GeV/c & $B = 5$ Tesla

- Image is a bit fuzzy in four spots around the azimuth and ellipse.

Data have no corrections. Fit a circle to a bunch of points without any initial guess. Fit determines $x_0$, $y_0$ and radius.
PID for $\theta_{\text{dip}} = 40^\circ$

Typical rms error (pion) $\sim 0.43$ mrad per single hit

- Focusing & smearing errors and ring distortion correction only.
- Larger dip angles have larger rms error.
Total error in our RICH design

<table>
<thead>
<tr>
<th>Npe ~18 for $\theta_{dip} = 4^\circ$, and 24 for $\theta_{dip} = 40^\circ$, both at 50 GeV/c</th>
</tr>
</thead>
</table>

Errors per single photon: $\sigma_{\text{single photon}} = \sqrt{(\sigma_{\text{chromatic}}^2 + \sigma_{\text{pixel}}^2 + \sigma_{\text{smearing/focusing}}^2)}$\text{single photon}

$\sigma_{\text{smearing/focusing}} \sim 0.25-0.4$ mrad; depends on momentum and dip angle

$\sigma_{\text{chromatic}} = 0.0009*(4.3-1.9)/\sqrt{12} \sim 0.62$ mrad – see appendix

$\sigma_{\text{pixel}} \sim [\text{pixel size}/\sqrt{12}]/\langle L_{\text{photon}} \rangle \sim 0.3-0.4$ mrad; $\langle L_{\text{photon}} \rangle$ is average photon path length (for 0.5 mm pixels size)

Common error: $\sigma_{\text{tracking}} \sim 0.3$ mrad or 0.1 mrad in case of SiD

Total error: $\sigma_{\theta/\text{track}} = \sigma_{\text{single photon}}/\sqrt{\text{Npe}} \otimes \sigma_{\text{tracking}} \sim 0.35$ mrad or $\sim 0.2$ mrad (SiD)

• PID performance: 2.5 $\sigma$ limit or 4.0 $\sigma$ limit (SiD) at $\sim 50$ GeV/c.
L=25 cm

**Error contribution for final error with FBK SiPMs**

(Use the overall standard deviation errors for each distribution, i.e., do not use fitted results)

<table>
<thead>
<tr>
<th>P [GeV/c]</th>
<th>$\theta_{\text{dip}}$ [deg]</th>
<th>Npe per track for pions</th>
<th>Chromatic error per photon hit [mrad]</th>
<th>Chromatic error per track [mrad]</th>
<th>0.5mm pixel error per photon hit [mrad]</th>
<th>0.5mm pixel error per track [mrad]</th>
<th>Focusing/smearing error per photon hit [mrad]</th>
<th>Focusing/smearing error per track after correction [mrad]</th>
<th>Track error [mrad]</th>
<th>Total $\theta_c$ error per track [mrad]</th>
<th>PID pi/K separation in number of sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>4</td>
<td>18</td>
<td>0.62</td>
<td>0.143</td>
<td>0.38</td>
<td>0.09</td>
<td>0.25</td>
<td>0.058</td>
<td>0.3</td>
<td>0.35</td>
<td>16.0</td>
</tr>
<tr>
<td>30</td>
<td>4</td>
<td>18</td>
<td>0.62</td>
<td>0.143</td>
<td>0.38</td>
<td>0.09</td>
<td>0.25</td>
<td>0.057</td>
<td>0.3</td>
<td>0.35</td>
<td>6.9</td>
</tr>
<tr>
<td>50</td>
<td>4</td>
<td>18</td>
<td>0.62</td>
<td>0.143</td>
<td>0.38</td>
<td>0.09</td>
<td>0.25</td>
<td>0.057</td>
<td>0.3</td>
<td>0.35</td>
<td>2.4</td>
</tr>
<tr>
<td>50</td>
<td>40</td>
<td>24</td>
<td>0.62</td>
<td>0.125</td>
<td>0.29</td>
<td>0.06</td>
<td>0.44</td>
<td>0.089</td>
<td>0.3</td>
<td>0.34</td>
<td>2.5</td>
</tr>
</tbody>
</table>

- After tracking error, chromatic error is the largest at present.
- In blue are parameters we can tune to influence RICH design.
### Error contribution for final error with FBK SiPMs

(Use the overall standard deviation errors for each distribution, i.e., do not use fitted results)

<table>
<thead>
<tr>
<th>P [GeV/c]</th>
<th>$\theta_{\text{dip}}$ [deg]</th>
<th>Npe per track for pions</th>
<th>Chromatic error per photon hit [mrad]</th>
<th>Chromatic error per track [mrad]</th>
<th>0.5mm pixel error per photon hit [mrad]</th>
<th>0.5mm pixel error per track [mrad]</th>
<th>Focusing/smearing error per photon hit [mrad]</th>
<th>Focusing/smearing error per track after correction [mrad]</th>
<th>Track error [mrad]</th>
<th>Total $\theta_c$ error per track [mrad]</th>
<th>PID pi/K separation in number of sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>4</td>
<td>18</td>
<td>0.62</td>
<td>0.143</td>
<td>0.38</td>
<td>0.09</td>
<td>0.25</td>
<td>0.058</td>
<td>0.1</td>
<td>0.21</td>
<td>26.5</td>
</tr>
<tr>
<td>30</td>
<td>4</td>
<td>18</td>
<td>0.62</td>
<td>0.143</td>
<td>0.38</td>
<td>0.09</td>
<td>0.25</td>
<td>0.057</td>
<td>0.1</td>
<td>0.21</td>
<td>11.4</td>
</tr>
<tr>
<td>50</td>
<td>4</td>
<td>18</td>
<td>0.62</td>
<td>0.143</td>
<td>0.38</td>
<td>0.09</td>
<td>0.25</td>
<td>0.057</td>
<td>0.1</td>
<td>0.21</td>
<td>4.0</td>
</tr>
<tr>
<td>50</td>
<td>40</td>
<td>24</td>
<td>0.62</td>
<td>0.125</td>
<td>0.29</td>
<td>0.06</td>
<td>0.44</td>
<td>0.089</td>
<td>0.1</td>
<td>0.18</td>
<td>4.6</td>
</tr>
</tbody>
</table>

- After tracking error, chromatic error is the largest at present.
- Now it really makes sense to reduce chromatic & pixel errors.

L=25 cm
Expected PID for $\theta_{\text{dip}} = 40^\circ$ at 50 GeV/c & $B = 5$ Tesla

• Tracking error really makes a difference.
• In this plot we consider all contributions to the final error.
Conclusion

- We have demonstrated that $\pi/K$ separation of $4.6\sigma$ is possible at 50 GeV/c & 5 T, if tracking direction error will be $\sim 0.1$ mrad.

- We find that the focusing effect error is larger than the magnetic smearing error for momenta larger than 20 GeV/c.

Next:

- Introduce a realistic SiPM noise to verify that timing cuts work.

Down the road challenges:

- Optimize optical design of the entire system considering all tracks.

- MC simulation of the entire system
Appendix
Each SPAD element has edge effects:

- Gola’s suggestion: Use micro-lenses to remove edge effect.
- Large arrays have slightly worse timing resolution:

  - Gola’s suggestion: Organize array differently to improve timing

• **0.5mm pixel SiPM can reach single photon timing resolution/pixel of \( \sigma \approx 25 \text{ ps} \).**
• **SPTR = single photon timing resolution, SPAD = Single photon avalanche diode, an element of SiPM**
Photon Detection Efficiency (PDE) of a single SiPM

Photon detection efficiency of single SiPM:
\[ \text{PDE} = \text{FF} \times \text{QE}(\lambda) \times P_T(V_{bias}, \lambda) \]

- \text{QE}(\lambda) – QE of Si
- \text{FF} – Fill factor within one SiPM
- \text{P}_T(V_{bias}, \lambda) – Trigger efficiency

SiPM array has additional losses due to gaps between pixel elements!
I assume 65%:

- We switched from Hamamatsu SiPM PDE in the calculation to FBK SiPM PDE.

This gives us a few photoelectrons extra!
Chromatic error: FBK vs. Hamamatsu

C4F10: Cherenkov angle for $\beta = 1$ and refraction index

- **FBK SiPM:** $\sigma_{\theta_c} |_{\text{single photon}} \sim \frac{d\theta_c}{dE} (E_2 - E_1) \frac{1}{\sqrt{12}} = 0.0009 \times (4.3 - 1.9) \frac{1}{\sqrt{12}} = 0.62 \text{ mrad} \Rightarrow \sigma_{\theta_c} |_{18 \text{ photons}} \sim 0.14 \text{ mrad}
Mirror choice for FBK SiPM


- So far, I kept a classical Al + MgF₂ + Cr coating. This coating was used by CRID.
- $N_{pc}$ is about the same for Cr + Al + HfO₂ coating; perhaps tiny reduction of chromatic error.
Final efficiency: FBK vs. Hamamatsu

- Al+Cr+HfO$_2$ coating helps in UV region, but it makes it worse in red region.
- It reduces chromatic error from 0.62 to 0.60 per photon hit. May consider it in future.
Timing for $\theta_{\text{dip}} = 4^\circ$ & 20 GeV/c & $B = 5$ Tesla

- Points near $\phi_c = 180^\circ$ have small time shift of ~25 ps.
- Note: This time correction was not used in this analysis.
Cherenkov rings for $\theta_{\text{dip}} = 4^\circ$ at 20 GeV/c with $B = 5$ Tesla

- "$t_1-t_0$" timing has almost no effect on the corrected Cherenkov angle.

$\sigma_{\text{start}} = 10$ ps
$\sigma_{\text{stop}} = 25$ ps
Cherenkov rings for $\theta_{dip} = 4^\circ$ at 20 GeV/c with $B = 5$ Tesla

- $f_c$ depends on time $t_1 - t_0$, but corrected $\theta_c$ does not.

$\sigma_{\text{start}} = 10$ ps
$\sigma_{\text{stop}} = 10$ ps

$(t_1 - t_0) = [\text{ps}]$

$\sigma_{\text{start}} = 10$ ps
$\sigma_{\text{stop}} = 25$ ps

$(t_1 - t_0) = [\text{ps}]$

$\sigma_{\text{start}} = 50$ ps
$\sigma_{\text{stop}} = 50$ ps

$\phi_{\text{azimuth}} \quad [\text{deg}]$

Corrected $\theta_c \quad [\text{deg}]$
Cherenkov rings for $\theta_{\text{dip}} = 4^\circ$ & 20 GeV/c with $B = 5$ Tesla

- 3D views of Cherenkov angle including ”$t_1$-t$_0$” timing.

$\sigma_{\text{start}} = 10$ ps
$\sigma_{\text{stop}} = 25$ ps
Cherenkov angle distribution for $20 \text{ GeV/c} \ & \ \theta_{\text{dip}} = 4^\circ \ & \ B = 5 \text{ Tesla}$

Note: I started to get “help” from AI computer (https://chat.openai.com/auth/login); he knows more about Mathematica than any person I know.

rms error = 0.25 mrad per single hit

- Fit histogram with 3 Gaussian distributions.
- $\sigma_3$ error dominates; $\sigma_1$ and $\sigma_2$ errors are smaller than rms error.
Magnetic field on & off for $20 \text{ GeV/c} \ & \ \theta_{\text{dip}} = 4^\circ$

rms error = 0.25 mrad per single hit

$B = 5 \text{ Tesla}$

$A_1 = 323.7$
$\text{Mean}_1 = 52.7 \text{ mrad}$
$\sigma_1 = 0.013 \text{ mrad}$
$A_2 = 185.6$
$\text{Mean}_2 = 52.7 \text{ mrad}$
$\sigma_2 = 0.063 \text{ mrad}$
$A_3 = 37.4$
$\text{Mean}_3 = 52.7 \text{ mrad}$
$\sigma_3 = 0.38 \text{ mrad}$

$B = 0.001 \text{ Tesla}$

$A_1 = 323.9$
$\text{Mean}_1 = 52.7 \text{ mrad}$
$\sigma_1 = 0.010 \text{ mrad}$
$A_2 = 205.5$
$\text{Mean}_2 = 52.7 \text{ mrad}$
$\sigma_2 = 0.058 \text{ mrad}$
$A_3 = 39.1$
$\text{Mean}_3 = 52.68 \text{ mrad}$
$\sigma_3 = 0.37 \text{ mrad}$

• “Magnetic field off” errors are smaller.
Smearing vs. focusing error at 20 GeV/c & $\theta_{dip} = 4^\circ$ & B = 5 Tesla

<table>
<thead>
<tr>
<th></th>
<th>Smearing error</th>
<th>Focusing error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_1$</td>
<td>0.008 mrad</td>
<td>0.010 mrad</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>0.024 mrad</td>
<td>0.058 mrad</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>0.09 mrad</td>
<td>0.37 mrad</td>
</tr>
</tbody>
</table>

(Result of subtraction of square of errors)

• We conclude that the focusing error is larger than the smearing error.
Cherenkov angle distribution for 50 GeV/c & $\theta_{\text{dip}} = 40^o$ & $B = 5$ Tesla

- $\sigma_3$ error dominates; $\sigma_1$ and $\sigma_2$ errors are smaller than rms error.
- Analyzing magnetic field off data, we again conclude that the focusing effect error is larger than the smearing effect error.

A_1 = 42.5
Mean_1 = 53.08 mrad
$\sigma_1 = 0.073$ mrad
A_2 = 61.2
Mean_2 = 53.06 mrad
$\sigma_2 = 0.158$ mrad
A_3 = 76.7
Mean_3 = 53.1 mrad
$\sigma_3 = 0.53$ mrad

rms error (pion) $\sim 0.43$ mrad
Magnetic field on & off for $50 \text{ GeV/c} \& \theta_{\text{dip}} = 40^\circ$

• Note: Errors are about the same for magnetic field off.
• We again conclude that the focusing effect error is larger than the smearing effect error.
Are digital SiPMs a good choice in future?

Peter Fisher, Heidelberg

- Can have very small pixel sizes.
- Combine electronics and photosensor together on one chip. Fill factor: 55%.
- Can switch off the cell which is too noisy.
- Can daisy chain different segments.
• Cerenkov imaging with our gaseous RICH is vastly superior.
Physics motivation $\pi/K/p$ particle identification

- **General point:** What is the origin of flavor? Why we have three families?
- **Higgs physics:** need to test Higgs coupling to lighter quarks. Use $\pi/K$ PID to separate strange-initiated jets from u/d (ArXiv: 2203.07535v2, Mar.2022)
- **Flavor physics:** requires excellent hadron particle identification (separation of $\pi$, K, p) to resolve combinatorics + separate decay modes
- **SM physics:** Plenty of $Z$, $W$, top produced! Measure $Z \rightarrow ss\bar{s}$, $Z \rightarrow qq$, $e^+e^- \rightarrow ss\bar{s}$, $W \rightarrow cs$, etc.

- **Additional references:**
  - Wolfgang Altmannshofer: [SSI2021](#) lectures on “Roles of Higgs Sector in Generation & Flavor Problem”. Lecture 1: [slides](#), [video](#); Lecture 2: [slides](#), [video](#)
  - Patrick Meade: [SSI 2022](#) lectures on “Fermion Generations”. Lecture 1: [slides](#), [video](#); Lecture 2: [slides](#), [video](#)
  - Su Dong: SLAC Snowmass Higgs WG Mar/2020: [Higgs Yukawa Couplings & Fermion Generation Puzzle](#)