Optical components for Cherenkov detectors

J. Va’vra, SLAC

All items between radiator and photocathode
Content

• **Gases, liquids, solids, optical glues and matching gels**
  - Refraction index = f(\(\lambda\))
  - Chromatic correction
  - Transmission = f(\(\lambda\))

• **Aerogel**
  - Scattering and absorption lengths

• **Mirrors**
  - Visible photons
  - VUV photons

• **Possible problems**
  - Radiation damage, radio-luminescence, yellowing from light exposure
  - Optical distortions in materials
  - Scintillation background
General comments about Cherenkov detectors

A beautiful thing about Cherenkov detectors is that their performance is basically determined by the refraction index, transparency of the medium, QE and angular resolution of photon detectors
Refraction index of the optical medium

The “phase refraction index”:

\[ n = n_{\text{phase}} = \frac{c}{v_{\text{phase}}} \]
- first appeared in the Snell’s law
\( v_{\text{phase}} = \) waveform speed in medium

The “group refraction index”:

\[ n_{\text{group}} = \frac{c}{v_{\text{group}}} = \left[ n - \lambda \frac{dn}{d\lambda} \right] \]
\( v_{\text{group}} = \) velocity at which wave packet, i.e., photon or energy or information, is propagated in medium
Importance of refraction index

Cherenkov angle: \( \cos \theta_c = \frac{1}{n\beta} \)

Cherenkov light production threshold: \( \gamma_t = \frac{1}{\sqrt{1-n^{-2}}} \)

N photons for \( \beta \sim 1 \) particles with charge \( Z \): \( N(cm^{-1}eV^{-1}) = 370Z^2(1-n^{-2}) \)

Reflectivity & transmission for 90° angle incidence:

\[
R = \left(\frac{n-1}{n+1}\right)^2 \quad T = \frac{(1-R)^2t}{1+R^2t^2}, t = e^{-\mu L}
\]

Velocity error:

\[
\left(\frac{d\beta}{\beta}\right)^2 = (\tan \theta_c)^2 + \left(\frac{dn}{n}\right)^2
\]

Error in \( \theta_c \) due to chromatic broadening:

\[
\sigma_{\theta_c}(E) = \frac{d\theta}{dn} \frac{dn}{dE} \quad \sigma_{\theta_c} = \frac{1}{n \tan \theta_c} \frac{dn}{dE} \quad \sigma_{\theta_c}^{(tot)} \quad \sqrt{(n^2-1)}
\]

Ideal PID separation for \( \beta \sim 1 \):

\[
N_{\sigma} \sim \left( m_1^2 - m_2^2 \right) / \left[ 2p^2 \sigma_{\theta_c(tot)} \sqrt{(n^2-1)} \right]
\]

Group velocity: \( v_{\text{group}} = c / n_{\text{group}} \)

Group index:

\[
n_{\text{group}} = n - \lambda \frac{dn}{d\lambda}, \quad n = n_{\text{phase}}
\]

Time-of-propagation:

\[
\text{TOP} = \frac{L_{\text{path}}}{v_{\text{group}}} \quad \text{dTOP} = L \lambda d\lambda \left| \frac{d^2n}{d\lambda^2} \right| / c
\]

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How to determine n & $\frac{dn}{dE}$?


Start from the Lorentz-Lorentz equation:

$$\frac{(n^2 - 1)}{(n^2 + 2)} = \alpha \cdot f(E)$$

where:

$$\alpha = \frac{4\pi}{3} \cdot R_B \cdot A \cdot \frac{\rho(\text{density})}{M(\text{mol.weight})} = 0.378(\text{cm}^3) \cdot \frac{\rho(g \cdot \text{cm}^{-3})}{M(g \cdot \text{mole}^{-1})}$$

Molar refractivity of a medium is usually fitted with two-pole Sellmeier function:

$$f(E) = \frac{F_A}{(E^2_A - E^2)} + \frac{F_B}{(E^2_B - E^2)}$$

These formulas are used to determine the refraction index

Dispersion is obtained by differentiating Lorentz-Lorenz equation in respect to energy:

$$\frac{dn}{dE} = \alpha \frac{(n^2 + 2)^2}{6n} \frac{df}{dE}$$
The chromatic error “$\sigma_{0c} (\text{chromatic})$” in $\theta_c$ is caused by $n = n(\lambda)$ or $n(E)$ dependence.

Differentiating “$\cos \theta_c = 1/\beta n(E)$” one gets:

$$\sigma_{\theta_c}(E) = \frac{\partial \theta}{\partial n} \frac{dn}{dE} \sigma_E = \frac{1}{n \tan \theta} \frac{dn}{dE} \sigma_E$$

A simple model of overall efficiency:

$$\sigma_E = \Delta E/\sqrt{12}$$

More realistic shape:

- The chromatic error can only be reduced by reducing $\Delta E$. However, this reduces number of photoelectrons $N_{pe}$. A compromise has to be found.
- Cherenkov angle resolution of a typical detector is dominated by the chromatic error.
- However, time can be used for the color tagging, and in this way one can reduce the chromatic error effect.
Refraction index and transmission of window materials


Refraction index calculation:

<table>
<thead>
<tr>
<th>Solid</th>
<th>$f(E)$</th>
<th>$E_A$ (eV)</th>
<th>$E_B$ (eV)</th>
<th>$F_A$ (eV$^2$)</th>
<th>$F_B$ (eV$^2$)</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaF$^{(a)}$</td>
<td>$(n^2 - 1)/(n^2 + 2)$</td>
<td>11.760</td>
<td>11.903</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fused quartz</td>
<td>$(n^2 - 1)$</td>
<td>10.666</td>
<td>46.411</td>
<td>228.71</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CaF$_2$$^{(b)}$</td>
<td>$(n^2 - 1)/(n^2 + 2)$</td>
<td>12.350</td>
<td>71.855</td>
<td>345.36</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CaF$_2$$^{(c)}$</td>
<td>$(n^2 - 1)$</td>
<td>12.922</td>
<td>17.301</td>
<td>464.25</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>LiF$^{(d)}$</td>
<td>$(n^2 - 1)/(n^2 + 2)$</td>
<td>16.784</td>
<td>260.718</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiF$^{(e)}$</td>
<td>$(n^2 - 1)$</td>
<td>12.968</td>
<td>12.968</td>
<td>101.76</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>MgF$_2$ O-ray$^{(e)}$</td>
<td>$(n^2 - 1)$</td>
<td>13.085</td>
<td>68.270</td>
<td>397.01</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>MgF$_2$ F-ray$^{(e)}$</td>
<td>$(n^2 - 1)$</td>
<td>13.640</td>
<td>93.952</td>
<td>466.82</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>


One can calculate refraction index from these constants.

Window transmission $T$:

$$ T = \frac{(1 - R)^2 t}{1 + R^2 t^2}, \quad t = e^{-\mu L} $$

$$ R = \left(\frac{n - 1}{n + 1}\right)^2 $$
Benzene was used by HRS; TMAE by DELPHI, SLD, OMEGA, CERES, JETSET and CAPRICE; TEA by CLEO; CsI by ALICE, ATLAS, COMPASS, HADES; Bialkali by HERA-B, DIRC, HERMES, Belle-II, CELEX.
Refraction index of noble gases
T. Ypsilantis & J. Seguinot, NIMA 343(1994)30


<table>
<thead>
<tr>
<th></th>
<th>H₂</th>
<th>He</th>
<th>Ne</th>
<th>N₂</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_A$ (eV)</td>
<td>12.88</td>
<td>22.389</td>
<td>17.419</td>
<td>13.414</td>
<td>13.084</td>
<td>11.50</td>
<td>8.885</td>
</tr>
<tr>
<td>$E_B$ (eV)</td>
<td>20.250</td>
<td>40.412</td>
<td>45.501</td>
<td>26.216</td>
<td>24.217</td>
<td>17.789</td>
<td>25.358</td>
</tr>
<tr>
<td>$F_A$ (eV²)</td>
<td>638.899</td>
<td>451.532</td>
<td>278.088</td>
<td>921.282</td>
<td>791.68</td>
<td>851.667</td>
<td>813.157</td>
</tr>
<tr>
<td>$F_B$ (eV²)</td>
<td>653.340</td>
<td>788.718</td>
<td>3655.882</td>
<td>3659.598</td>
<td>3793.994</td>
<td>4034.683</td>
<td>10960.59</td>
</tr>
</tbody>
</table>

Two-pole Sellmeier formula:

$$f(E) = \frac{F_A}{(E^2 - E_1^2)} + \frac{F_B}{(E^2 - E_2^2)}$$

Refraction index of gas and liquid phase are related through this equation:

$$\frac{n^2 - 1}{n^2 + 2} = \left(\frac{p}{RT}\right)_{\text{gas}} \cdot \left(\frac{M}{\rho}\right)_{\text{liq}} \cdot \left(\frac{n^2 - 1}{n^2 + 2}\right)_{\text{liq}}$$

- **Note:** P. Glassel’s plot was made using the parameterization in Tom’s paper. A few constants differ slightly in Eugenio’s paper.
Refraction index of $C_nF_{2n+2}$ Freon liquids

Seguinot J. et al., CERN-LEPC 82-59 and DELPHI 82-23; see also CERN-EP/89-92 and LPC/89-25.

$n = a + b \, E$

for $5 \leq E \leq 7$ eV

<table>
<thead>
<tr>
<th>Molecule</th>
<th>a</th>
<th>$b \times 10^3$</th>
<th>$\rho_{\text{liq}}$</th>
<th>$M$</th>
<th>$T_b$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(eV$^{-1}$)</td>
<td>(g/cm$^3$)</td>
<td>(g/mol)</td>
<td>(K)</td>
<td>(7 eV)</td>
</tr>
<tr>
<td>CF$_4$</td>
<td>1.2039</td>
<td>4.75</td>
<td>1.603</td>
<td>88</td>
<td>146</td>
<td>1.2372</td>
</tr>
<tr>
<td>C$_2$F$_6$</td>
<td>1.1956</td>
<td>7.46</td>
<td>1.608</td>
<td>138</td>
<td>195</td>
<td>1.2478</td>
</tr>
<tr>
<td>C$<em>4$F$</em>{10}$</td>
<td>1.2037</td>
<td>10.25</td>
<td>1.594</td>
<td>238</td>
<td>265</td>
<td>1.2754</td>
</tr>
<tr>
<td>C$<em>5$F$</em>{12}$</td>
<td>1.2109</td>
<td>7.85</td>
<td>1.63</td>
<td>288</td>
<td>303</td>
<td>1.2658</td>
</tr>
<tr>
<td>C$<em>6$F$</em>{14}$</td>
<td>1.2177</td>
<td>9.28</td>
<td>1.68</td>
<td>338</td>
<td>329</td>
<td>1.2827</td>
</tr>
</tbody>
</table>

Note: ALICE data were done after it was found that their Cherenkov rings were inconsistent with the refraction index from J.S.

- How do we resolve the discrepancy between two sets of values for C$_6$F$_{14}$?
To reproduce beam test results, ALICE group asked Ohara, company specializing in these kind of tests, to measure the C$_6$F$_{14}$ refraction index. Their values were found to be consistent with data of Maltezos (Delphi), Kaplan (NIST), STAR and ALICE data.

**ALICE & STAR used this parameterization:** $1.177 + 0.0172 \times \frac{12400}{\lambda}$ (\lambda in Å).
• The 1-st FDIRC prototype used Kamland oil to couple to Fused Silica.
• DIRC bar boxes used Epotek-301-2 epoxy to glue bar boxes together.
• FDIRC optics used Shin-Etsu RTV SES-403 to couple to bar boxes.
• Panda was using Marcol 82 mineral oil in their early prototype.
- Epotek 301-2 optical epoxy was used to glue together DIRC bar together.
- Shin Etsu RTV 403 was used to couple FBLOCK to new wedge in the FDIRC prototype.
Chromaticity $K_2\text{CsSb}$ Bialkali photocathode

S. Hallensleben et al. Optical Communication, 180 (2000) 89, and
D. Motta and S. Schonert, NIM A 539 (2005) 217

Refraction index:

- **Refraction index** = $n$ (phase index) + $i \cdot k$ (absorption loss).
Angular and polarization dependence of the reflectance of KaCsSb bialkali photocathode

M.E. Moorhead, N.W. Tanner, Oxford Univ., NIMA 378 (1996) 162

Laser reflections from various boundaries:

- The measured refraction index $n = n_3 + i . k_3 = 2.7 \pm 0.1 + i (1.5 \pm 0.1)$ at 442 nm wavelength.
- They show that it is important to take the polarization into account.

Total reflection:

J. Va'vra, Optical components
Chromatic correction
Chromatic broadening of Cherenkov light in quartz

Quartz at ~ 420 nm:

<table>
<thead>
<tr>
<th>n_{phase}</th>
<th>n_{group}</th>
</tr>
</thead>
<tbody>
<tr>
<td>~1.4681</td>
<td>~1.5065</td>
</tr>
</tbody>
</table>

\[
\cos \theta_c = \frac{1}{(n \beta)};
\]
\[
v_{\text{group}} = c / n_{\text{group}} = c / [n - \lambda \frac{dn}{d\lambda}]:
\]
\[
\theta_c (\text{red}) < \theta_c (\text{blue})
\]
\[
v_{\text{group}}(\text{red}) > v_{\text{group}}(\text{blue})
\]

Calculation: \( \Delta \theta_c = f(d_{\text{TOP}}/L_{\text{path}}) \)
(can be calculated with a spreadsheet)

Data from the 1-st FDIRC prototype:

Data from final FDIRC prototype:
D. Roberts et al.: FDIRC contribution to this conference

- The Cherenkov angle chromatic error can be corrected by time.
- FDIRC: \( \theta_c \) is improved using timing; TORCH: time is improved using \( \theta_c \) information.

\( 12/4/13 \)
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Transmission
Transmission of Fluorocarbon liquids

Y. Andres et al., NIM A 486 (2002) 590; Albrecht at al., NIMA 502 (2003) 266

- COMPASS C\textsubscript{4}F\textsubscript{10}, Delphi C\textsubscript{5}F\textsubscript{12}, STAR C\textsubscript{6}F\textsubscript{14} purity are the best of all working RICH detectors so far. C\textsubscript{7}F\textsubscript{16} and C\textsubscript{8}F\textsubscript{18} was an old FCRID detector R&D (NIMA 433(1999)527).
Example of excellent analysis for $\text{C}_4\text{F}_{10}$ gas

O. Ullaland, RICH 2004

- This plot is a result of a fit.
~20 years earlier: Transmission of Fluorocarbon liquids was worse


- ~20 years earlier, $C_6F_{14}$ & $C_5F_{12}$ transmissions were worse than today, and Delphi had better transmission than CRID. Why?
- Antonello Di Mauro and Martyn Davenport’s comments: (a) One can buy now much cleaner $C_6F_{14}$ (PF5060-DL quality), (b) change molecular sieve size from 13X down to 4 or 5 Å, (c) use “copper catalysts” supplied by Michael Bosteels at CERN, (d) avoid using Oxisorbs as it could react with partially fluorinated contaminants, (e) use $N_2$ gas bubbling through $C_6F_{14}$ to remove oxygen, (f) use s.s. tubing. Delphi avoided Oxisorbs, as G. Lenzen did not get consistent results.
- CRID used only Oxisorb to clean $C_6F_{14}$.

12/4/13 J. Va'vra, Optical components
Light collection system features: (a) by using aspheric lenses off-axis distortions were minimized, (b) easy to fabricate plastic lenses, (c) molded production is cheap, (d) integrated into the support structure, (e) was able to handle high HERA-B rates, after TMAE-based detector failed due to aging.
Transmission in quartz
3M Co. fiber data sheets, and DIRC R&D effort: NIM A515(2003)680

• DIRC Fused silica is made of so called “wet” quartz, i.e., high OH content, which exhibits a good transmission in the UV region, but not in the near infrared spectrum.
• DIRC quartz transmission is dominated by the Rayleigh scattering (I ∼ 1/λ⁴).
• DIRC quartz is mostly Fused silica Spectrasil-2000 made by Thermo Sydicate.
Rayleigh scattering in DIRC bars

Scattering on a particle with diameter $d$
Aerogel: particle is a solid ball clump of SiO$_2$, separated by voids (pores)

$$I = I_0 \frac{1 + \cos^2 \theta}{2R^2} \left( \frac{2\pi}{\lambda} \right)^4 \left( \frac{n^2 - 1}{n^2 + 2} \right)^2 \left( \frac{d}{2} \right)^6$$

(Valid for a condition: $\pi d << \lambda$)

**DIRC bars:** Rayleigh scattered fraction $\sim 1 - e^{-\alpha d}$, determine $\alpha \sim 730808.75 / \lambda^4$
from NIMA 515(2003)680, $\lambda$ is a wavelength in [nm], $d$ is bar length [cm]

$$I = I_0 \frac{8\pi^4\alpha^2}{\lambda^4 R^2} (1 + \cos^2 \theta)$$
($\alpha$ is molecular polarizability)

Reflected photon has the same energy but different direction:

Lord Rayleigh (John William Strutt), (1842–1919)

- For DIRC bar of length $\sim 5-10$ meters a photon loss is only 1-3\% at 400 nm.
1mm-thick RTV samples (Rhodorsil 141 & Shin-Etsu SES-403) are very transparent.
- Epotek 301-2 epoxy cuts off the optical acceptance in DIRC & FDIRC.
- FDIRC prototype used Epotek-301-2 epoxy and Shin-Etsu RTV SES-403.
Internal reflection coefficient

- Surface polish quality
- Pollution of surfaces
Int. reflection coefficient on polished quartz bars


The internal reflection coefficient is measured absolutely with this technique:

\[
((0, -1)r^2 - L_1)r' = I_i
\]

which in turn leads to:

\[
I_i = I_o + x \cdot I_o + x' \cdot I_o
\]

Its solution is related to the coefficient of internal reflection \( r \) through the following equation:

\[
x' = r' \cdot \exp\left(\frac{r^2}{L} \cdot \sqrt{1 + \left(\frac{r}{r^2}\right)^2}\right)
\]

\[
= \text{(Reflection coef.)} \cdot \text{Transmission coef.}
\]

Scalar theory:

(J. Melson et al., App. Optics & Eng., Vol VII)

Total integrated scatter =

\[
\sim (4 \pi \delta \cos \theta_o/\lambda)^2
\]

\( \delta \) - rms height of surface microregularities (5-15 Å)

R – fraction of scatter at an angle \( \theta_o \)

R_o – fraction of reflected light into all angles

DIRC and Panda measured bar internal reflection coefficient:

SLAC data consistent with surface polish of 6-7 Å rms, except below 350 nm.

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FDIRC camera: oil or Fused silica?

- Critical components limiting performance: (a) Epotek 301-2 epoxy, (b) internal reflection coeff. in bars (one has to worry about a polish and pollution of bar surfaces), and (c) mineral oil.
- 1-st FDIRC prototype used Kamland oil (80v% $\text{C}_{12}\text{H}_{26} + 20v\% \text{C}_{9}\text{H}_{12})$, MiniBooNE used Marcol 7, and Panda DIRC prototype used Marcol 82.
- There is a shift in $\theta_c$ towards smaller values by 0.5-1 mrads between forward and backward bouncing photons (photons are getting more red).

J. Va'vra, Optical components 12/4/13
Refraction index dependence of density:

\[ n = 1 + k \rho \]

- \( n \) - refraction index
- \( \rho \) - Aerogel density
- \( k \) - constant (0.213 at 400 nm)

Two important quantities to consider:

**Scattering length** \( L_{\text{scat}} \): determined by internal structure (pores), which have significantly smaller size than the wavelength \( \lambda \) of incoming light. \( L_{\text{scat}} \) follows the **Rayleigh law**: \( L_{\text{scatt}} \sim \lambda^4 \).

**Absorption length** \( L_{\text{abs}} \): controlled by impurities, \( L_{\text{abs}} \gg L_{\text{scatt}} \).
History of Aerogel

- **Aerogel was invented by S. S. Kiestel in 1931** (J. Phys. Chem. 34, 52, 1932), College of the Pacific, Stockton, CA.
- This was followed by a long history of development, a process, which is still continuing to this date.
- One of the best insulator and lowest density solid material.
- Chemical structure of the ordinary aerogel is SiO$_2$ with small 1-5% contamination of the water depending on the baking procedure. Thus, atomic and nuclear properties of aerogels are almost the same as for quartz.

**Typical transmission dominated by Rayleigh scattering in UV region:**

**Major contributor to Rayleigh scattering: pores**

![Graph showing transmission dominated by Rayleigh scattering in UV region](http://energy.lbl.gov/ECS/aerogels/sa-pore.html)

This edge is limited by Rayleigh scattering:

$$I \sim \frac{1}{\lambda^4}$$

- **By modifying the Aerogel chemistry, one can control a number and size of pores, and in this way one can control the Aerogel transparency to some degree. One seeks a good ratio of “unscattered Cherenkov photons” to “scattered photons.”**
- **To achieve a good N$_{pe}$/ring, the aerogel tile thickness should to be at least 4 cm.**
Novosibirsk Aerogel development
A.F. Danilyuk et al., NIMA 494(2002)491

Transmittance & scattering length:

\[ T = A \exp \left( -\frac{d}{L_{sc} (\lambda/400)^4} \right) \]

- \( T \) – transmittance
- \( D \) – Aerogel thickness
- \( L_{sc} \) – scattering length
- \( \lambda \) – wavelength [nm]
- \( A \) – surface scattering coefficient (0.9-0.96)

<table>
<thead>
<tr>
<th>Refractive index</th>
<th>1.008</th>
<th>1.03</th>
<th>1.05</th>
<th>1.08</th>
<th>1.13</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{sc} ) (mm)</td>
<td>42</td>
<td>54</td>
<td>55</td>
<td>44</td>
<td>19</td>
</tr>
</tbody>
</table>

Absorption:

- Aerogel transmittance is very small compared to Fused silica.

\[ L_{absorption} \gg L_{sc} \text{ for } \lambda > 300 \text{ nm} \]
Belle-II Aerogel development
Ichiro Adachi, Belle-II review, 2011

Transmittance & scattering length = f(\lambda):

- Pin-drying technique seems to improve the UV transparency.
- Transmittance is getting large for \lambda > 400-500 nm. One wants to use more red-sensitive detector.

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Mirrors

- Internal reflection
- External reflection
Examples of mirror reflectivity

**FDIRC mirrors on FBLOCK surfaces** (Company’s data):

- FDIRC: FBLOCK's mirror reflectivity


- FDIRC mirrors on FBLOCK surfaces (Company’s data):

- DIRC mirrors at the end of each bar (NIMA, A 515 (2003) 680):

- FACT aluminum mirrors (H. Anderhub et al., NIM A 639 (2011) 58):

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Possible problems

- Gas scintillation
- Optical distortions in quartz
- Radiation damage of quartz
- Radiation damage of glues
- Damage of glues by UV light
Scintillation in CF$_4$, C$_2$F$_6$, C$_4$F$_{10}$, CH$_4$ and Ar gases

R. Gernhauser et al., NIM A371(1996)300

Photon excitations were stimulated by proton ($E_p = 22$ MeV), O$_{16}$ ($E_O = 80$ MeV) ion beams, and $\alpha$’s from Am$^{241}$ source ($E_\alpha = 5.485$ MeV):

- CF$_4$ scintillation near 240 and 300 nm prohibits of using it as a Cherenkov radiator. LHCb is adding CO$_2$ to CF$_4$ to reduce this effect. CO$_2$ is apparently quenching the CF$_4$ scintillation.
- Scintillation level in C$_4$F$_{10}$ or C$_2$F$_6$ gases is acceptable. No significant light yield from CH$_4$.

S. Biagi: ~99% emissions come from molecular fragments F* and CF$_3$*
Optical distortions in early DIRC quartz

J. Cohen-Tanugi et al., NIMA, A 515 (2003) 680

Typical stria in an ingot (Suprasil):

- One should check for optical distortions in quartz volume.
- However, one can say that the quartz uniformity has improved since, thanks to requirements by the lithography.

Observe a diffraction pattern in laser tests:

100 µm dia. wire:

Diffraction with a He-Ne laser in Suprasil Standard:
One can see (a) slow variation of refraction index across the ingot’s depth, and (b) fast variation with a ZYGO interferometer. However, both samples did not reveal the stria structure using a simple laser test.

- Stria exist in every quartz, but there is a variation in their magnitude. The Fused silica intended for lithography has a variation of \( n \) to less than \( \sim 0.1 \) ppm peak-to-peak, FBLOCK for FDIRC specification: Slow variation of refraction index in the direction of the boule’s depth: \( < 5-10 \) ppm.

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J. Va'vra, Optical components
Quartz sensitivity to UV light and radiation

• **This point comes from the lithography requirements:** Ultra-pure silica SiO$_2$ is sensitive to breakage of O-links by the UV light. Once the O-bond is broken, such molecule tend to create the color center, unless the glass has plenty of hydrogen around, which tends to fill the missing void. If hydrogen fills the void to form the SiOH molecule, the quartz remains transparent. It is a kind of “repair”, which becomes effective if the quartz is loaded by at least $\sim 10^{17}$ H$_2$-molecules/cm$^3$. For example, Corning 7980 Fused Silica, used for the FDIRC camera optics intended for SuperB, has this level of hydrogen in it.

• Matthias Hoek’s results, presented at RICH 2010, are consistent with the above point (M. Hoek, NIMA 639(2011)227), however, he also makes additional point that adding too much of hydrogen may affect the transmission:

![Graphs showing transmission and absorption length as functions of hydrogen concentration.](image)
Radiation damage of Fused Silica

Sample made of Spectrosil 2000: 20.7 cm long sample

Spectrosil 2000 long rods: 137 cm long rods

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Type</th>
<th>Visual change</th>
<th>Radioluminescence</th>
<th>Transmission loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitreosil-F</td>
<td>TSL</td>
<td>Natural</td>
<td>No (100 krad)</td>
<td>No (100 krad)</td>
<td>Severe (7 krad)</td>
</tr>
<tr>
<td>T-08</td>
<td>Heraeus Amersil</td>
<td>Natural</td>
<td>Yellow (330 krad)</td>
<td>Yes (330 krad)</td>
<td>Severe (10 krad)</td>
</tr>
<tr>
<td>JGS3-IR</td>
<td>Beijing Institute</td>
<td>Natural</td>
<td>Brown (400 krad)</td>
<td>No (400 krad)</td>
<td>Severe (20 krad)</td>
</tr>
<tr>
<td>Suprasil</td>
<td>Heraeus Amersil</td>
<td>Synthetic</td>
<td>No (280 krad)</td>
<td>Yes (280 krad)</td>
<td>Small (280 krad)</td>
</tr>
<tr>
<td>JGS1-UV</td>
<td>Beijing Institute</td>
<td>Synthetic</td>
<td>No (650 krad)</td>
<td>No (650 krad)</td>
<td>No (650 krad)</td>
</tr>
<tr>
<td>Spectrosil 2000</td>
<td>TSL</td>
<td>Synthetic</td>
<td>No (180 krad)</td>
<td>No (180 krad)</td>
<td>Small (180 krad)</td>
</tr>
<tr>
<td>Spectrosil B</td>
<td>TSL</td>
<td>Synthetic</td>
<td>No (254 krad)</td>
<td>Yes (254 krad)</td>
<td>Small (254 krad)</td>
</tr>
</tbody>
</table>

- DIRC Fused Silica bars (Spectrosil 2000) are made of so called “wet” quartz (high OH content).
Radiation damage of optical glues
J.Va’vra, R. Kirby, M.McCulloch, SuperB R&D, M. Hoek, Glasgow, Private communication

- DIRC used Epotek 301-2 epoxy. FDIRC used Epotek 301-2 epoxy and Shin-Etsu 403 RTV.

12/4/13
J. Va’vra, Optical components
Matthias Hoek: a substantial damage starts occurring above $\sim 10^{19}$ photons/cm$^2$.

During the DIRC R&D effort, we have noticed that the Epotek-301-2 optical epoxy will yellow just sitting in the lab. See DIRC note #39 for more details.

Nicolas Arnaud has analyzed the BaBar DIRC data, and found no evidence that the Epotek glue was affected by radiation during a period of $\sim$10 years.
Optical aberration to $\theta_c$ in DIRC bars


**Chromatic error:** $\sim 3-4$ mrad

**Pixel size** ($\sim$6mm x 6mm pixels): $\sim5.5$ mrad

**Optical aberrations:** 0 mrad (at ring center) to 9 mrad (in outer wings of Cherenkov ring)

This pattern was discovered by our student J. Benitez during the 1-st FDIRC prototype development:

- The optical aberration (kaleidoscopic pattern) is due to a square bar acting on pieces of the ring, and this is amplified by the mirror effect.