Optical properties of RICH detectors

J. Va’vra

SLAC National Accelerator Laboratory, CA 94025, USA

Abstract – In this review article we discuss the optical components in RICH detectors. In particular we mention transmission and refraction index in gases, liquids, solids, optical glues, matching gels and Aerogel. We mention a few examples of mirror reflectivity in UV and visible region. We also discuss radiation damage, radio-luminescence, yellowing from light exposure, optical distortions in materials, and scintillation.

INTRODUCTION

A beautiful thing about Cherenkov detectors is that their transparency of the medium, QE and angular resolution of performance is basically determined by the refraction index, transmission and refraction index in gases, liquids, solids, optical glues, matching gels and Aerogel. We mention a few examples of wave’s phase, especially in far UV region. To determine the energy propagates more slowly through a medium than the between two indices for the Fused silica; one can see that the velocity of wave energy.2

One deals with two refraction indices. The “phase refraction index” is defined by: 

\[ n = n_{\text{phase}} = c / v_{\text{phase}} \]

where \( v_{\text{phase}} \) is waveform speed in the medium; it appeared first in the Snell’s law. The “group refraction index” is defined by:

\[ n = n_{\text{group}} = (n_{\text{phase}} - \lambda \cdot dn/d\lambda) \]

where \( n_{\text{group}} \) is propagation velocity of wave energy.2

\[ (n^2 - 1) / (n^2 + 1) = \alpha \cdot f(E) \] (1)

where \( \alpha = 0.378 \text{cm}^2/g \cdot \text{cm}^3 \cdot \text{mol}^{-1} \cdot \text{g}^{-1} \) and \( f(E) \) is the molar refracitivity, usually fitted with two-pole Sellmeier function:

\[ f(E) = \frac{F_A}{(E_A^2 - E^2)} + \frac{F_B}{(E_B^2 - E^2)} \] (2)

Numerical values of \( F_A, F_B, E_A \) and \( E_B \) for typical Cherenkov detector materials can be found in these two references [1,2].

One can now calculate many quantities. For example, a transmission \( (Tr) \) of thin a window of thickness \( (L) \) can be calculated using these two equations:

\[ R = \left( \frac{n - 1}{n + 1} \right)^2, \quad Tr = \frac{1 - R^2}{1 + R^2}, \quad t = e^{-\mu L} \] (3)

where \( (R) \) is reflectivity and \( (\mu) \) is attenuation length.

![Energy dependence of two refraction indices in the Fused silica.](image)

Fig. 1 Energy dependence of two refraction indices in the Fused silica.

Figure 1 shows a typical wavelength-dependent difference between two indices for the Fused silica; one can see that the energy propagates more slowly through a medium than the wave’s phase, especially in far UV region. To determine the phase refraction index, one starts from the Lorentz-Lorenz equation:

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

where \( \alpha = 0.378 \text{cm}^2/g \cdot \text{cm}^3 \cdot \text{mol}^{-1} \) and \( f(E) \) is the molar refracitivity, usually fitted with two-pole Sellmeier function:

\[ f(E) = \frac{F_A}{(E_A^2 - E^2)} + \frac{F_B}{(E_B^2 - E^2)} \]

Numerical values of \( F_A, F_B, E_A \) and \( E_B \) for typical Cherenkov detector materials can be found in these two references [1,2].

One can now calculate many quantities. For example, a transmission \( (Tr) \) of thin a window of thickness \( (L) \) can be calculated using these two equations:

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

where \( (R) \) is reflectivity and \( (\mu) \) is attenuation length.

Figure 2 shows a history over past 30 years of a refraction index \( (n-1) \) of various radiators, transmission \( (Tr) \) of typical window materials and the photocathode quantum efficiency \( (QE) \) of typical windows, radiators and photocathodes. 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 detectors.

An important group of radiator materials are Freon liquids \( C_n F_{2n+2} \). Their refraction index can be described simply as

---

1 Invited talk at RICH 2013, December 4, Kamakura, Japan
2 Ibn Sahl, was the first astronomer to use the Snell’s law accurately when building his lenses in Baghdad (940-1000 a.d.). The phase index was introduced by W. Snel van Royen (Willebrord Snellius), a Dutch astronomer (1580-1626). The group velocity concept was introduced ~200 years later by W. Hamilton, an Irish astronomer (1805–1865).

This work supported by the Department of Energy, contract DE-AC02-76SF00515.
\[ n = a + b \cdot E \], for photon energy range \( 5 \leq E \leq 7 \text{ eV}, \) as shown on Fig. 3a [4]. During the ALICE experiment beam tests, a different slope was found for the \( \text{C}_2\text{F}_{14} \) liquid in the same energy interval: \( n = 1.177 + 0.0172 \cdot \lambda (\text{Å}) \) [5]. This was followed by more measurements, and a summary is shown on Fig. 3b. One can notice that the refraction index energy dependence is non-linear if a larger photon energy window is used.

A knowledge of the refraction index of various Freon liquids as measured by Delphi [3] and ALICE [4]. (b) Summary of all measurements for the \( \text{C}_2\text{F}_{14} \) liquid for a larger energy range. The refraction index does not follow a simple linear relationship if a larger photon energy window is used [4-7].

Table 1: Sellmeier parameters (2) for noble gases [2].

<table>
<thead>
<tr>
<th></th>
<th>( \text{H}_2 )</th>
<th>( \text{He} )</th>
<th>( \text{Ne} )</th>
<th>( \text{N}_2 )</th>
<th>( \text{Ar} )</th>
<th>( \text{Kr} )</th>
<th>( \text{Xe} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_0 ) (eV)</td>
<td>12.88</td>
<td>22.387</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_a ) (eV)</td>
<td>20.25</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_0 ) (eV)</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_a ) (eV)</td>
<td>653.230</td>
<td>788.718</td>
<td>3625.882</td>
<td>3659.598</td>
<td>3793.594</td>
<td>4034.683</td>
<td>10960.59</td>
</tr>
</tbody>
</table>

Table 1 shows constants for the Sellmeier function (2) for noble gases [2]. Refraction index of gas and liquid phase are related through equation (4), where \( p \) is gas pressure, \( T \) is temperature, \( R \) is a gas constant, \( M \) is molecular weight and \( \rho \) is a liquid density.

\[
\frac{n^2-1}{n^2+2} = \left( \frac{p}{RT} \right)_{\text{gas}} + \frac{M}{\rho} \left( \frac{p}{n^2+2} \right)_{\text{liq}} + \frac{n^2-1}{n^2+2} \left( \frac{p}{n^2+2} \right)_{\text{liq}} (4)
\]

A knowledge of the refraction index of various optical couplings between different materials is crucial for all optical designs as they influence the photon reflection, a phenomenon especially important at large incidence angles to glue/window interfaces. Figure 4a shows examples of refraction indices of several coupling materials relative to the Fused silica. For example, BaBar DIRC bars were glued together with the Epotek-301-2 epoxy, the 1-st FDIRC prototype used the Kamland oil to couple to Fused Silica (one can see that it is pretty good match to Fused silica), final FDIRC prototype used Shin-Etsu RTV SES-403 to couple its optics to the DIRC bar boxes, Belle-II TOP counter is using Norland 61 epoxy, and Panda prototype used Marcol 82 mineral oil. Figures 3b&c show the measurement of the Epotek 301-2 optical epoxy and the Shin-Etsu SES-403 RTV. As one can see, some people use uncured epoxy, cured epoxy is made in a form of a wedge to enable laser-based deflection measurements.

Fig. 5 shows the refraction index of the \( \text{K}_2\text{CsSb} \) Bialkali photocathode, which can also influence reflection and absorption [9]. Its real part (n) describes the phase refraction index, and the imaginary part (k) describes the absorption.

---

1. Both STAR and ALICE experiments are using this new parameterization.
2. ALICE group asked Ohara Co. to measure the \( \text{C}_2\text{F}_{14} \) refraction index. Their values were found to be consistent with data of Maltezos [6], Kaplan [7].
The refraction index is influencing the chromatic broadening of the Cherenkov angle, which is typically limiting the performance. The chromatic error contribution to the Cherenkov angle $\sigma_{\theta_c}$ is calculated by differentiating equations \( \cos \theta_c = 1/\beta n(E) \), and the Lorentz-Lorenz equation (1) \[1\]:

$$\sigma_{\theta_c} = \frac{\partial \theta}{\partial n} \frac{dn}{dE} \sigma_E = \left( \frac{1}{n \tan \theta} \right) \left( \frac{(n+2)^2}{6n} \frac{df}{dE} \right) \sigma_E$$  \[5\]

The chromatic error is reduced by reducing $dn/dE$ and $\sigma_E$. Decreasing $\sigma_E$ results in a decreased number of photoelectrons. The best way to reduce the chromatic error is by choosing a detector with a longer wavelength response. The error $\sigma_E$ is determined by the detector overall response. For example, Fig. 6 shows energy response of FWHM~1eV for the 1-st FDIRC prototype \[10\], and equation (5) gives $\sigma_{\theta_c} \sim 4.5 \text{ mrad}$.

New fast DIRC-like RICH detectors can correct the chromatic error using timing – see Fig. 7. This idea was pioneered for the first time by the 1-st FDIRC prototype \[10\]. Figure 7a,b shows the principle. A red photon is faster than the blue photon and their time of arrival to a given pixel can be measured with a fast detector. One can determine a correlation between $d\theta_c = \theta_c(\lambda) - \theta_c(\lambda_{\text{ref}})$ and $d\text{TOP}/L_{\text{path}} = \text{TOP}/L_{\text{path}}(\lambda) - \text{TOP}/L_{\text{path}}(\lambda_{\text{ref}})$, where TOP is time of propagation in quartz, $L_{\text{path}}$ is photon path length and $\lambda_{\text{ref}}$ is a reference wavelength, taken in the middle of acceptance. If the Cherenkov angle is measured well ($\sigma(\theta_c) \sim 10 \text{ mrad}$) with timing resolution of $\sim 200 \text{ ps}$ or better, one can correct the chromatic error. One can reduce the Cherenkov angle error by $\sim 1 \text{ mrad}$ typically.

**TRANSPARENCY OF A MEDIUM**

To achieve a good UV medium transparency is often a highly non-trivial problem. In case of gases and liquids, it requires mastering sophisticated filtering methods, which requires many years of experience, and understanding possible

---

\[5\] Similar results obtained with the final FDIRC prototype (talk by D. Roberts).
impurities. Figures 8a,b,c illustrate this problem in case of liquid Freons such as C\textsubscript{6}F\textsubscript{10}, C\textsubscript{8}F\textsubscript{12} and C\textsubscript{12}F\textsubscript{14}. The first experiments to use them on a larger scale was Delphi and CRID at SLD. But it took 10-15 years to achieve the ultimate purity in experiments such as STAR\textsuperscript{6}, ALICE and COMPASS. One can summarize the improvements\textsuperscript{7} as follows: (a) one can buy now much cleaner C\textsubscript{6}F\textsubscript{14} (PF5060-DL quality), (b) change molecular sieve size from 13X down to 4 or 5 Å, (c) use “copper catalysts”, (d) avoid using Oxisorbs as it could react with partially fluorinated contaminants, (e) use N\textsubscript{2} gas to bubble through C\textsubscript{6}F\textsubscript{14} to remove oxygen, and (f) use stainless steel tubing. Delphi already avoided Oxisorbs\textsuperscript{16}, as they did not get consistent results, but CRID did use Oxisorbs to clean the C\textsubscript{6}F\textsubscript{14} liquid, which may have been a mistake - see Fig. 8b. Figure 8c shows a level of depth one has to go into to understand the C\textsubscript{6}F\textsubscript{10} transparency quantitatively.

\textsuperscript{6} The STAR collaboration benefited from a collaboration from several Delphi people, who had a long-term experience with the Freon purification. 
\textsuperscript{7} I thank for these comments to A. Di Mauro and M. Davenport.

---

**Fig. 8** (a) Transmission of various C\textsubscript{n}F\textsubscript{2n+2} Freon liquid radiators. We quote only the best achieved results\textsuperscript{10-12, 5}. (b) The transmission of C\textsubscript{6}F\textsubscript{12} & C\textsubscript{12}F\textsubscript{14} achieved only ~15 years earlier\textsuperscript{14-15}. (c) Reconstruction of measured C\textsubscript{6}F\textsubscript{10} transmission by fitting contributions from various contaminants\textsuperscript{16}. 

---

**Fig. 9** Transmission of 3-mm thick UV-plastic, used for HERA-B photon camera lenses\textsuperscript{17}. 

One can consider a UV-plastic for certain applications. For example, the HERA-B experiment used such plastic for the photon camera lenses\textsuperscript{17} with a good transmission – see Fig. 9. Light collection system had these features: (a) by using aspheric lenses off-axis distortions were minimized, (b) easy to fabricate, (c) molded production is cheap, (d) were able to handle high HERA-B rates, after TMAE-based detector failed due to aging.

**Fig. 10** Transmission of several RTVs, Epotek-301-2 optical epoxy, Fused silica matching gel, all relative to the transmission of a quartz substrate\textsuperscript{18}. We also show BK-7 glass and the Bialkali photocathode QE. Each glue sample was imbedded between two 3.1 mm-thick quartz pieces made of natural quartz.

Figure 10 shows a transparency of several optical glues considered for FDIRC for SuperB\textsuperscript{18}. One can see that a 1mm-thick RTV samples Rhodorsil 141 or Shin-Etsu SES-403, are very transparent. The Epotek 301-2 epoxy limits the DIRC optical acceptance.

As Fig. 11a shows, the Epotek-301-2 optical epoxy can be damaged by UV photons\textsuperscript{8} if one exceed a limit of ~10\textsuperscript{19} photons/cm\textsuperscript{2} \textsuperscript{19}; the damage by Co\textsuperscript{60} is shown on Fig. 11b\textsuperscript{18}. Detailed anlysis of the BaBar DIRC data found no evidence that the Epotek glue was affected by radiation during a period of ~10 years.\textsuperscript{9} One should nevertheless worry about damaging the instrument like this during machine physics runs. Fig. 11c shows that Shin-Etsu 403 RTV can be damaged also\textsuperscript{18}.

\textsuperscript{8} During the DIRC R&D effort, we have noticed that the Epotek-301-2 optical epoxy will yellow just sitting in the lab under fluorescent light.
\textsuperscript{9} BaBar DIRC data analysis performed by N. Arnaud.
Fused silica is far from a "unique material", as there are many different grades available, with various different additives and impurities, different transmittances in different ranges of the wavelength spectrum. Figure 12 shows an example of this complexity. For example, the “wet” fused silica, with a large amount of OH-molecules, is suitable for working in the UV regime such as DIRC, on the other hand, the “dry” fused silica, with no OH-content and minimum of other impurities, is useful for IR regime for fiber applications. For “wet” fused silica absorption in the IR regime is domination by OH-absorption peaks. Both DIRC Spectrosil-2000 bars or FDIRC’s Corning 7980 are made of so called “wet” quartz; Corning 7980 is loaded with 800-1000ppm of OH-molecules, while other impurities are less than 1ppm. For this type of Fused silica the transmission is dominated by the Rayleigh scattering below ~600nm.

As one can see in Table 2, the radiation damage of Fused silica is also complicated. Generally more pure materials have lower damage. Typically natural quartz, such as used in the CRID experiment [14], has a severe radiation damage and such material is not suitable for modern high luminosity machines. However, even ultra-pure silica SiO$_2$ is sensitive to breakage of O-links by UV light and radiation. 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 ~10$^{17}$ H-atoms/cm$^2$. For example, Corning 7980 Fused Silica, used for the FDIRC camera optics intended for SuperB, has 800-1000ppm of OH-molecular content (by weight), and less than 1000ppb of other impurities. M. Hoek’s transmission measurements are consistent with the above point, but he makes an additional point that adding too much of hydrogen may affect the transmission negatively [20].
INTERNAL REFLECTION COEFFICIENT

DIRC-like detectors have to deal with a large number of internal reflections (up to 1500), and to have acceptable losses, one requires a very high internal reflection coefficient close to ~0.9997. This can be achieved if a Fused silica bar is polished to ~5 Å rms. The internal reflection coefficient was measured absolutely with a “calorimetric” method [21]. As shown in Fig. 13, this method measures five light intensities and uses the number of light bounces, the bar dimensions and the bulk attenuation as inputs.

The internal reflection coefficient has a direct effect on the wavelength acceptance in the DIRC-like devices. For photons with many bounces, the wavelength response shifts toward red wavelengths. Figure 14 shows this effect, calculated for 100, 500 and 1000 bounces for the 1-st FDIRC prototype [10].

Fig. 14 The internal reflection coefficient starts limiting the transmission of DIRC-like detectors, such as the FDIRC prototype, for a large number of photon bounces — the detector becomes more and more sensitive to red wavelengths [10].

AEROGEL

The Aerogel has a long history of development, a process, which is still continuing to this date more than 80 years after the invention. It is the best insulator and lowest density solid material. Since the refraction index follows the equation is \( n = k \rho \), one can reach very small values \( n = 1.008 \) - 1.15 (\( k = 0.213 \) at 400nm). There are two important quantities to consider: (a) scattering length \( L_{\text{scat}} \), which is determined by internal structure (pores) and follows the Rayleigh law, and (b) absorption length \( L_{\text{abs}} \), which is controlled by impurities; generally \( L_{\text{abs}} \gg L_{\text{scat}} \).

The chemical structure is SiO\(_2\) with small 1-5% contamination of the water depending on the baking procedure. The atomic and nuclear properties of aerogels are almost the same as for quartz. By modifying the Aerogel chemistry, one can control a number and size of pores, and in this way one can control the Aerogel transparency.

Figure 15 shows an example of a technique, so called pin-drying technique, which seems to improve the Rayleigh UV-edge transparency and the transmission length of the Aerogel [22].

Fig. 15 (a) Transmittance and (b) transmission length at 400 nm for conventional method and so called pin drying technique to prepare Aerogel, as obtained in the Belle-II R&D effort [24].

Fig. 16 (a) Transmittance of 4cm-thick Aerogel tile for various types of materials of different refraction index and the scattering length, as obtained in the Novosibirsk R&D effort [25]. The transmittance is clearly considerably worse than what would obtain from the Fused silica.

For Aerogel, the Rayleigh scattering occurs on particles of diameter “d” consisting of solid ball clumps of SiO\(_2\) separated by voids (pores), and follows the formula (valid for \( \pi d \ll \lambda \), which is easily satisfied since \( d < 10 \) nm typically):

\[
I = \frac{1 + \cos^2 \theta}{2 \lambda^2} \left( \frac{2\pi}{\lambda} \right)^4 \left( \frac{n^2-1}{n^2+2} \right)^2 \left( \frac{d}{2} \right)^6 \tag{6}
\]

To minimize the scattering, one minimizes the diameter \( d \). One should point out that the Aerogel formula for the Rayleigh scattering for solid Fused silica differs from equation (6), as it is due to scattering on molecules (SiO\(_2\)), and follows this equation:

\[
I = I_0 \frac{\sin^2 \theta}{\lambda^4 R^2} (1 + \cos^2 \theta) \tag{7}
\]

One seeks a good ratio of “unsattered Cherenkov photons” to “scattered photons.”

---

10 Aerogel was invented in 1931 by Samuel S. Kistler, American scientist and chemical engineer, (1900–1975)
11 Lord Rayleigh (John William Strutt), (1842–1919)
The transmittance (Tr) and the scattering length (L\textsubscript{scatt}) are related to each other as follows:

\[ Tr = A \exp \left[ \frac{x}{L_{\text{scatt}}(\lambda/400)^4} \right] \]

where \( x \) is the Aerogel thickness, \( A \) is the surface scattering coefficient (0.9-0.96) [25]. To achieve a good \( N_{\text{pe}}/\text{ring ratio}, \) the aerogel tile thickness should be at least 4 cm, and for this thickness the scattering length is a significant factor in the transmittance. This is illustrated in Fig. 16, which shows that the transmittance of 4 cm-thick Aerogel tiles are considerably worse than what one would get from Fused silica of the same thickness.

A significant new improvement,\(^{(12)}\) utilizing the Aerogel detector concept, first published in Ref. [27], is stacking together several layers of Aerogel tiles (see Fig. 17), each with different refraction index, to achieve a focusing effect, and therefore improve the Cherenkov ring resolution. Several groups have now accepted this concept [24, 26, 27].

Fig. 17 A stack of five Aerogel tiles, each one with different refraction index, to achieve focusing [26].

**MIRRORS**

Figure 18 shows four examples of mirror reflectivity from four different applications. It is clear that mirrors operating in visible range are relatively straightforward, however, mirrors operating in far-UV are the most difficult to use – see Fig. 18c.

\[ \frac{\lambda}{400} \]

\[ \frac{x}{L_{\text{scatt}}} \]

\[ \exp \left[ \frac{x}{L_{\text{scatt}}(\lambda/400)^4} \right] \]

Fig. 18 Mirror reflectivity for (a) BaBar DIRC at the end of each bar (external reflectivity mirror) [21], (b) FDIRC focusing block internal reflectivity mirrors [28], (c) COMPASS mirrors operating in far-UV regime [29], and (d) FACT aluminum mirrors working in air [30].

**OPTICAL ABBESSIONS**

We would like to conclude the paper by mentioning two optical effects one should be aware of when designing fused silica optics.

The first effect is a diffraction-like pattern, called ‘‘lobes’, observed in early DIRC bars [21]. Fig. 19a shows a model of the structure of the optical inhomogeneity, where it is assumed that there are curved ‘‘layers’’ of varying index of refraction within the fused silica ingots from which the bars are produced – see Fig.19b. If a laser beam were traveling tangent to these layers, then it would, in effect, see a ‘‘diffraction grating’’ formed by the alternating layers of high and low refraction index, thereby producing lobes – see Fig.19c. This effect is observed in many early samples of both types of synthetic fused silica considered for use in the DIRC: Heraeus Suprasil and QPC Spectrosil. The ‘‘lobe effect’’ must be taken very seriously because it can cause photon losses or image distortion of the Cherenkov light. Because of its bright lobes and the angular range over which they are produced, Heraeus Suprasil was rejected for use in the DIRC. QPC Spectrosil fused silica was deemed acceptable both because of its lower lobe power and also since the lobes in the QPC fused silica are only produced at angles close to perpendicular to the bar axis, which are not relevant for the photons detected in the DIRC.

The fused silica material’s optical inhomogeneity has improved considerably since the DIRC construction, thanks to improvements in the lithography. For example, the FDIRC camera optics [31] used the Corning 7980 fused silica, which had the refraction index variation of less than 10 ppm – see Fig.20. No lobes were observed with a laser.

The second effect we want to mention is so called kaleidoscopic effect discovered during the 1-st FDIRC

\(^{(12)}\) The idea was originally introduced independently by T. Iijima and by S. Korpar.
The optical aberration ranges from 0 mrad (at ring center) to \(-9\) mrad (in outer wings of Cherenkov ring), i.e., it is a significant effect, comparable to the chromatic error in magnitude, and has to be considered seriously. Figure 21a show the anatomy of the Cherenkov ring images for z-positions along the bar length. We tried to reduce the kaleidoscopic effect with various types of focusing with no success [33] – see Fig. 21b. Even non-focusing DIRC has it, uniformly spread along the ring. It will be interesting if one come up with an optical design, which will remove this aberration.

![Fig. 19](image_url)

**Fig. 19** (a) Model of the periodic structure of the optical inhomogeneity within raw ingot, (b) actual periodicity observed under the microscope (with overlayed 7\(\mu\)m wire), and (c) observed diffraction with a laser [21].

![Fig. 20](image_url)

**Fig. 20** FDIRC camera [31] optics used Corning 7980 fused silica, which had the refraction index variation of less than 10 ppm.\(^{13}\) Although refraction index has a modulation, no laser diffraction was observed in this material [32].

### SCINTILLATION AND RADIO-LUMINESCENCE

It is not desirable if a radiator scintillates when charged particles are passing through. Ref. [34] did show that CF\(_4\) gas radiator scintillates the most of typical gases – see Fig. 22. This is due to emissions from molecular fragments F\(^*\) and CF\(_3\)* [35].

A considerable effort was spent during the DIRC R&D stage to prove that the DIRC bar fused silica does not scintillate when a muon traverses the bar [36].

In addition to transmission loss, radio-luminescence was also observed in quartz as consequences of radiation damage; Table 2 summarizes all these observations [21]. The radio-luminescence is a known property of quartz and fused silica [37]. This effect was found to be negligible for the DIRC final fused silica choice [21].

![Fig. 21](image_url)

**Fig. 21** (a) Cherenkov ring images at a dip angle of 90\(^\circ\) as a function of track distance along the bar length, starting at \(z = 0\), closest point to the focusing block. Number of kaleidoscopic images grows step by step [31]. (b) Kaleidoscopic images for different mirrors in FDIRC camera and BaBar DIRC (no mirror) [10].

![Fig. 22](image_url)

**Fig. 22** Scintillation in various gases. Notice that CF\(_4\) gas scintillates the most [34]. 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).

\(^{13}\) The most expensive Corning fused silica material, used in the lithography, has the refraction index variation of less than 0.1 ppm. This level was judged as unnecessary for the FDIRC camera.
REFERENCES

[32] Corning Co. information, 2009