The use of fluorocarbon radiators in the Delphi RICH detectors

G. Lenzen, E. Schyns, J. Thadome, J. Werner ¹

Abstract

The DELPHI experiment at LEP is equipped with Ring Imaging Cherenkov (RICH) detectors in the barrel and forward regions in order to provide particle identification over nearly the full solid angle. The use of fluorocarbons as Cherenkov radiators will be discussed.

Contribution to the First Workshop on RICH Detectors, Bari, Italy, 1993

¹Present address : BKA Wiesbaden, Germany

1 Introduction

Ring Imaging CHerenkov (RICH) detectors [1, 2, 3] are used to identify hadrons in the momentum range of 0.5 GeV/c up to 50 GeV/c in the DELPHI experiment [4, 5] at the LEP storage rings at CERN. This necessitates two radiator systems with different indices of refraction. The Cherenkov light created in liquid and gas radiators is detected by photon detectors of the time projection chamber (TPC) type. The photosensitive agent is TMAE, Tetrakis(Dimethylamino)Ethylene $C_2[(CH_3)_2N]_4$, with an ionization potential of 5.64 eV. Heavy fluorocarbons (C_6F_{14} as liquid, C_4F_{10} and C_5F_{12} as gas radiators) serve as media in which charged particles produce Cherenkov light. These media should be transparent from 5.64 eV to the quartz window cut-off at 7.50 eV. The above fluorocarbon media show only small chromatic aberrations. In addition these media are non-flammable, non-toxic, thermally stable and usually chemically inert.

Some properties of the DELPHI RICH radiators are given in table 1. The index of refraction is n , the threshold value of $\gamma = 1/\sqrt{1 - \beta^2}$ being defined as $\gamma_{th} = \sqrt{1/(1 - 1/n^2)}$, and θ_{max} being the Cherenkov angle for a $\beta = v/c \approx 1$ particle.

	boiling point °C	n at 7 eV	$(dn/dE) * 10^6 \text{ eV}^{-1}$ 6.5-7.5 eV	γ_{th}	θ_{max} mrad
C_4F_{10}	- 2	1.001530	53	18.3	55.6
C_5F_{12}	28	1.001720	51	16.9	59.1
C_6F_{14}	57	1.283	9300	1.61	677.1

Table 1: *The properties of the fluorocarbons used in DELPHI*

While C_6F_{14} is used as liquid Cherenkov radiator medium in both Barrel and Forward RICH detectors, C_4F_{10} serves as Forward RICH, and C_5F_{12} as Barrel RICH gas radiator. The better UV transparency of C_4F_{10} in comparison to C_5F_{12} and the longer radiator length of the Forward RICH (58 cm) in comparison to the Barrel RICH (< 40 cm) compensate for its lower refractive index. The number of expected photoelectrons is therefore about the same for the forward and barrel parts of the DELPHI RICH detectors. Because of its low boiling point, C_4F_{10} requires no heating of the detector. The short radiator length of the Barrel RICH leads to the choice of the C_5F_{12} with its higher refractive index at the price of having to maintain the detector at about 40°C.

The DELPHI RICH fluid systems are composed of two parts:

1. The Barrel RICH fluid system [6] consisting of:
 - a gas radiator volume of about 24 m³ filled with saturated perfluoropentane C_5F_{12} ,
 - a liquid radiator circuit of 48 radiators of 5 l each filled with saturated perfluorohexane C_6F_{14} , and
 - a circuit of 24 pairs of drifttubes with a volume of 50 l per pair containing the detector gas of 75 % methane, 25 % ethane, and a small amount of the photosensitive agent TMAE.
2. Two endcap Forward RICH fluid systems, each consisting of:
 - a gas radiator volume of about 4 m³ of saturated perfluorobutane C_4F_{10} ,
 - a liquid radiator circuit of 36 radiators of about 1 l each filled with C_6F_{14} , and
 - a driftvolume circuit with 12 driftboxes of 20 l volume each, filled with pure ethane and a small amount of TMAE.

The three fluid systems are completely independent from each other. The liquid and gas radiator circuits of the Barrel and of both Forward RICH detectors are recirculating, while their drift gases are distributed in non-recirculating circuits.

A description of the three fluid systems can be found elsewhere [7]. The gas radiator media (C_5F_{12} and C_4F_{10}) are stored as liquids in stainless steel tanks of 500 l, and twice 100 l respectively. The appropriate liquid is evaporated into the gas radiator where it replaces slowly the radiators' nitrogen atmospheres. Turbo pumps suck the gas out of the radiators, lead it to purifiers, and then to condensers, where the gases are liquified again and fall back into the main storage tanks. The fluorocarbon gases can be purified in their liquid phases as well.

The filling of the Barrel RICH gas radiator with C_5F_{12} is surveyed by a sonar-based device which provides an online monitor of the composition and stability of the nitrogen- C_5F_{12} gas mixture by measuring the sound velocity of the mixture [8][9]. This instrument is situated at the exit of the gas radiator. Figure 1 shows that the whole Barrel RICH gas radiator is filled with C_5F_{12} after about 12 hours and after one volume exchange only.

The liquids (C_6F_{14}) for both Barrel and Forward RICH detectors are also stored in stainless steel tanks, from where pumps drive the liquid through purification systems. From there each radiator tray is individually filled through up to 25 m long stainless steel capillaries with an internal diameter of 1.5 mm. After having filled the radiators, the liquid C_6F_{14} falls into 10 mm internal diameter nitrogen filled collector lines, and returns into the storage tank.

2 The Transparencies of the Fluorocarbons in the UV Region

When the DELPHI detector started data-taking in 1989, two manufacturers could deliver big quantities of perfluoropentane C_5F_{12} ¹⁾ and perfluorohexane C_6F_{14} ²⁾. A good UV transparency of these RICH radiators is mandatory for a high number of Cherenkov photons per event.

The quality of a batch was tested by receiving a small sample (typically 1 l) of that batch. The UV transparency was measured with the DELPHI monochromator system. These non-treated samples of liquid C_5F_{12} and C_6F_{14} showed a rather poor transmission in the UV region. After recirculation through a small OXISORB ³⁾ cartridge for some hours, the samples were cleaned from oxygen and water traces, so that the UV transparency had improved considerably. The first sample of perfluorobutane C_4F_{10} ⁴⁾ was received at the end of 1989. The very good UV gas transparency [10] after cleaning with OXISORB lead to the decision to use C_4F_{10} as gas radiator for the Forward RICH detectors.

1) C_5F_{12} : 3M Co. St. Paul, MN 55144, USA, under the trademark FC87 or PF5050
RTZ Chemicals, ISC Division, Bristol, UK, under the trademark PP50

2) C_6F_{14} : 3M Co. under the trademark FC72 or PF5060
RTZ Chemicals under the trademark PP1

3) Messer Griesheim Co., D-4000 Düsseldorf, Germany

4) C_4F_{10} : 3M Co. St. Paul, MN 55144, USA, product code DP L-12321

C5F12 FILLING BARREL RICH

Figure 1: Filling of the Barrel RICH gas radiator

2.1 The DELPHI RICH Monochromator System

The quality of the Cherenkov gases and liquids has to be known on-line during data taking. Their UV transparency is measured with monochromators [9]. There are three systems in total, one for the Barrel RICH and one each for the two Forward RICH detectors.

Each monochromator system is designed to measure up to four UV transparencies simultaneously: the liquid C_6F_{14} , the gases C_4F_{10} or C_5F_{12} , the driftgases C_2H_6 or a mixture CH_4/C_2H_6 , and the driftgases with TMAE.

The monochromator ⁵⁾ has 20 cm focal length. It is designed specifically to cover the wavelength region from about 100 nm to at least 250 nm. It uses a concave holographic grating as its single reflecting surface. The optical system is similar to the Seya-Namioka design. Only a simple rotation of the grating is required to change the wavelength.

The light from a projecting deuterium lamp ⁶⁾ is wavelength-selected by the grating of the monochromator. A beam divider consisting of three CaF_2 windows each tilted by 45° partially reflects the selected beam into three variable metal bellow cells.

The length of the cell for the C_6F_{14} liquid can be varied by 1.5 cm, while the short and long positions of the cells for the gas radiators and the drift gases differ by 15 cm. The remaining part of the unreflected beam is traversing the 2.5 cm long variable cell which measures the TMAE loaded driftgases.

Photomultipliers ⁷⁾ designed for single photon counting are installed at the end of each cell. All photomultipliers are covered with a wavelength shifter (1 μ m paratherphenyl and 25 nm MgF_2) in order to fit the spectral response to the operational region of 160 nm to 220 nm.

The readout system consists of a 60 MHz amplifier/discriminator mounted in the photomultiplier housing. It converts the anode pulse into a differential ECL signal to be read out by a LeCroy 125 MHz counter. The monochromator systems are controlled by G64 through thinwire Ethernet communication.

Manifolds of valves connect different points of the appropriate parts of each fluid system -in general the entries and exits of the gases and liquids- with the variable monochromator cells.

2.2 The Cleaning of Fluorocarbon Radiators and Related Problems

Measurements with the monochromator system show that the fluorocarbon materials as delivered by the manufacturers are not sufficiently transparent in the UV region to be directly used as Cherenkov radiators. As water and oxygen are optical absorbers in the spectral range from 160 nm to 190 nm, the fluorocarbons have to be cleaned by molecular sieves ⁸⁾ and catalysts ⁹⁾ to get rid of the water and oxygen contamination.

Nearly all fluorocarbons are sold by the manufacturers under internal trademark, rarely under their chemical composition names. Though the above fluorocarbons should be fully saturated -i.e. they should contain only carbon and fluorine- other compounds may be present which may contain additional atomic species. Only fully saturated per-fluorocarbons are known to be stable and chemically inert. Only these should be cleaned by a catalyst.

⁵⁾ Minuteman Model 302-VM

⁶⁾ Hamamatsu 30W type L 1626

⁷⁾ EMI 9884B

⁸⁾ Type 13X-8/2, Chemische Fabrik Uetikon, Switzerland

⁹⁾ Dispersed copper C61-1-R, Catalyst and Chemicals, Brussels, Belgium

In 1992 it was found that some batches of perfluorohexane (C_6F_{14}) would chemically react with the catalyst which resulted in a large unacceptable loss of UV transparency. Chemical and physico-chemical techniques, i.e. distillation, UV-visible and FT-IR spectrometry were used to identify the causes of this chemical reaction mechanism. It could be shown that the reaction is due to a contamination with incompletely fluorinated molecules (general formulae $C_nH_xF_{2n-x}$) [11]. As the violent reaction between the catalyst and the oxygen in the gas or liquid could endanger the optimal operation of the detector, a non-aggressive inert cleaning system to remove both oxygen and water from perfluorohexane was successfully tested, the capillary membranes [12]. This device consists of a bundle of capillaries mounted in a stainless steel container. The liquid to be cleaned passes through the capillaries and the permeating substances (oxygen and water) are removed by pumping on the surrounding space of the capillaries. The working principle is based on permeating properties of different molecules with various kinetic diameters.

Two other non-aggressive cleaning methods for removing oxygen from liquid C_5F_{12} and C_6F_{14} were tested and shown to work: flushing the liquid with nitrogen and ultrasonic degassing [13].

Recently delivered batches of C_5F_{12} and C_6F_{14} show already a very good UV transparency. Therefore only molecular sieve cartridges of about 5 kg are used to improve the quality of the liquids.

2.3 Results

All three fluorocarbons (C_4F_{10} , C_5F_{12} , and C_6F_{14}) were measured with the same monochromator system in the spectral region from 160 nm to 220 nm. The UV transparencies of C_4F_{10} and C_5F_{12} were measured with the 15 cm variable gas cell at 40°C and atmospheric pressure, while the UV transparencies of C_6F_{14} and liquid C_5F_{12} were determined with the 1 cm liquid cell of the monochromator system at 25°C and atmospheric pressure.

The integrated measured transparency curve may indicate a good quality of the fluorocarbons. A 100 % transparent liquid or gas in the spectral range from 1600 Å to 2200 Å would lead to an integral value of 600 Å. Integral values of more than 400 Å for the liquid transparencies and of more than 520 Å for the gas transparencies are regarded as indications for good Cherenkov radiator qualities.

Typically, after a week of circulation of the gases and liquids through the radiators and purification systems there are no dramatic differences anymore between the qualities at the entrances and exits of the RICH detectors.

Figure 2 gives UV transparencies for the three fluorocarbons used in the DELPHI RICH detector after recirculation of one week. The bottom curve in each plot of figure 2 shows the product of the measured transparency curve with the absolute TMAE quantum efficiency curve [14]. The numbers of the integrated transparency curve and the integrated product of the transparency curve with the absolute TMAE quantum efficiency curve is given inside each subplot of figure 2.

Figure 2: Fluorocarbon transmissions

2.4 Figure of Merit (N_0)

The above UV transparency measurements can be used to estimate the expected number of photoelectrons N_{pe} in a RICH detector [15], which is determined by

$$N_{pe} = N_0 L \sin^2 \theta$$

where N_0 is the so-called figure of merit which is defined by

$$N_0 = 370 \int \eta(E) Q(E) R(E) T(E) dE [cm^{-1}]$$

where:

L is the radiator length in cm,

θ is the Cherenkov angle, depending on the refractive index n (taken at 7 eV),

$\eta(E)$ is the electron detection efficiency,

and $Q(E)$, $R(E)$ and $T(E)$ are the absolute quantum efficiency for photon conversion, the reflectivity of the mirror and the transmission of several detector components (radiator gas, quartz windows, drift gas, etc.) respectively.

Here N_0 is defined under the assumption of perpendicular particle incidence, unlimited acceptance and $\eta(E)=1$.

All wavelength dependent transmissions of materials were measured for perpendicularly incident UV-light, whereas in the actual experiment the angle of incidence varies widely. In addition dead space, internal total reflection in the quartz windows, conversion depth and attenuation length of TMAE, dead time of the preamplifiers and efficiency of the cathodes of the MWPC, Lorentz angle, and last but not least the reconstruction efficiency of Cherenkov photoelectrons in hadronic jets have to be taken into account. All these factors may lead to a significant loss in the number of photoelectrons per event. Only a detailed Monte Carlo program can reliably predict this number.

Table 2 presents the results for the figures of merit for the DELPHI Barrel and Forward RICH detectors, when only the measured qualities of the detector elements, like transmissions of the radiator gas and liquid, transmission of quartz, transmission of detector drift gas, mirror reflectivity, and TMAE quantum efficiency are considered. The electron detection efficiency $\eta(E)$ was set to 1, and the velocity of the charged particle is $\beta \approx 1$.

$N_0[cm^{-1}]/N_{pe}$	Barrel RICH C_5F_{12} and C_6F_{14}	Forward RICH C_4F_{10} and C_6F_{14}
gas radiator	81.6 / 11.1	89.6 / 15.6
liquid radiator	70.0 / 27.5	70.0 / 27.5

Table 2: The figures of merit N_0 and the number of expected photoelectrons N_{pe} under the assumption of full electron detection efficiency

The mean number of detected photoelectrons per muon event with momentum > 40 GeV/c in the DELPHI experiment is 8 for the Barrel RICH gas radiator, and 13 for the Barrel RICH liquid radiator. In the Forward RICH there are 12 photoelectrons detected from the gas radiator, and 8 photoelectrons from the liquid radiator. These numbers are closely predicted by detailed Monte Carlo studies [3], which take into account all the above mentioned effects. The number of detected photoelectrons follows Poisson statistics. The experimental resolutions are close to those given by the Monte Carlo calculations.

3 Acknowledgements

We would like to thank all our collaborators in DELPHI for their encouragement. We are especially grateful for the constant interest and support by U.Amaldi and J.Drees. M.Bosteels' contribution to the layout of the RICH fluid system is acknowledged with thanks. We express our thanks to S.Ilie for his guidance in the fluorocarbon purification. G.Hallewell is thanked for many fruitful discussions.

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