The ePIC dRICH radiator gas

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Abstract

The ePIC experiment at the EIC requires excellent particle identification in a wide phase space range. Particularly in the forward region, a wide momentum range has to covered. To this end hadron identification will be provided by a dual radiator RICH (dRICH) using as radiators aerogel and a fluorocarbon gas.

The optical properties of hexafluoroethane (C_2F_6), the gas proposed as dRICH radiator gas have been investigated. The main characteristics of the dRICH gas system and its proposed components which also minimize the environmental impact of the system operation are discussed. The preferred option to separate the components of the gas mixture is the use of selective permeability membranes instead of distillation.

Alternative options to C_2F_6, including the use of pressurized argon radiator, are considered as backup solutions, and dedicated prototype tests are ongoing.

The tools and techniques for qualifying and continuously monitoring the radiator gas are described, including a modified Jamin interferometer for precise determination and high accuracy monitoring of the refractive index.

Keywords: Ring Imaging Cherenkov Counters, Cherenkov radiator gas, Selective permeability membranes, Fluorocarbons

1. Introduction

The ePIC experiment at the future Electron–Ion Collider [1] is designed to investigate the internal structure of nucleons and nuclei with unprecedented precision, using a hermetic, multi-purpose detector that incorporates state-of-the-art tracking, calorimetry, and particle identification technologies.

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Hadron identification in the forward region covering the pseudorapidity range $1.5 < \eta < 3.5$ will be performed by the dual radiator Ring Imaging Cherenkov (dRICH) detector [2], expected to provide $\pi - K$ separation in the momentum range between 3 and 50 GeV/c and to supplement electron and positron identification from a few hundred MeV/c up to about 15 GeV/c.

The ePIC dRICH design is compact and combines SiO_2 aerogel radiator (≈2.5 m^2) with hexafluoroethane (C_2F_6) gas radiator (≈ 12 m^3). A wall of spherical mirrors, divided in six sectors, will focus the Cherenkov light on the photon detectors [3], based on SiPMs, arranged in a curved surface configuration and operated at low temperature (≈-40°C).

The high granularity SiPM-based photon detectors and the low chromaticity of C_2F_6 are the key elements to achieve the challenging high-mementum hadron identification goal of ePIC.

The properties of hexafluoroethane have been investigated and compared to those of the commonly used perfluorobutane (C_4F_{10}) radiator gas. Simulations have shown that despite the significantly lower average number of expected photons per ring (≈60%) and the almost identical ring angle resolution, C_2F_6 will offer increased $\pi - K$ discrimination power in the range of interest, namely up to 50 GeV/c due to the larger $\pi - K$ Cherenkov angle separation (≈0.9 mrad for C_4F_{10} and ≈1.2 mrad for C_2F_6 for a 50 GeV/c hadron). T

Strong requirements on the dRICH gas system are posed by the challenging separation of C_2F_6 from standard neutral gases and its high global warming power. A large effort is devoted to minimize the environmental impact of the ePIC dRICH.

The use of selective-permeability membranes for gas mixture separation offers an attractive alternative to distillation, and is presently considered to be the default option for the dRICH gas system. In fact, distillation is challenging using C_2F_6 due the the specific characteristics of its phase diagram.

The possibility of using gases alternative to hexafluoroethane is being investigated and the option to design a RICH capable of operating with pressurized argon is among the dRICH risk mitigation measures.

Dedicated tools and techniques for qualifying and continuously monitoring the radiator gas have been prepared, based on the experience of previous RICH detectors and new developments. A prototype of modified Jamin interferometer for precise determination of the refractive index value and for very accurate monitoring has been built and tested, showing that a resolution of the order of ten parts per billion can be achieved with this instrument. The requested resolution for dRICH performance according to the requirements for ePIC is of the order of 1 ppm.

2. Optical properties of hexafluoroethane

Hexafluoroethane has been selected as dRICH radiator gas for its refractive index value (n=1.00086 at STP) [4] and extremely low chromatic dispersion (dn/dλ=0.2×10^{-6} nm^{-1} at 350 nm), optimal for the ePIC dRICH

C_2F_6 was adopted as a Cherenkov radiator gas in the past [5] but it is not currently employed in any high-energy physics experiment.

Recent simulation studies and measurements performed with a dRICH prototype at the CERN test-beam facility [6] have provided a preliminary validation of the ePIC dRICH gas choice.

A key property of a Cherenkov radiator is its transparency in the wavelength range to which the photodetectors are sensitive; for the dRICH SiPMs this corresponds to 300–800 nm. Using the monochromator setup (see Fig. 1) of the COMPASS/AMBER RICH at CERN, a measurement has been performed in the VUV wavelength range with C_2F_6 of quality 5.0: a transparency

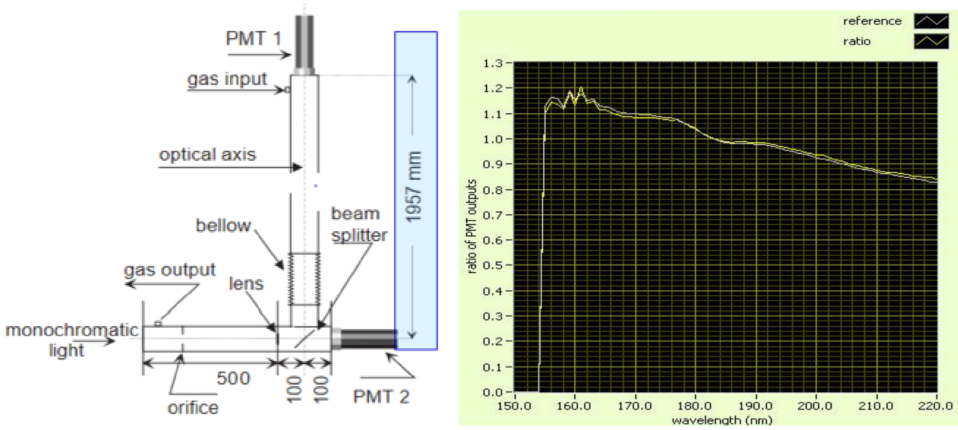

Figure 1: ()Left) Scheme of the COMPASS RICH transparency measurement device: a monchromatic light beam is split between a direct and a≈ 2 m long absorption columnn, both ending with a PMT. (Right) The ratio of the currents of the two PMTs is potted versus wavelength: in white the reference curve and in yellow the C_2F_6 absorption measurement curve. The transparency is larger than 98% over the whole measured range.

Figure 2: Setup for the monitoring of the C_2F_6 transparency in the 200-900 nm wavelength range.

larger than 98% have been observed in the 170-220 nm range, even for gas stored in bottles for long time (≈4 years).

A system based on a commercial spectrophotometer and a compact high-pressure cell with fused-silica windows (rated up to 10 bar) (see Fig. 2) has been developed to measure gas transparency over the 200–900 nm wavelength range. It will also be implemented as part of the continuous monitoring instrumentation of the dRICH gas system.

The scintillation properties of C_2F_6 are a source of concern for the use of this gas in an environment characterized by intense ionizing radiation. The impact of a photon background on the expected dRICH PID resolution is studied using simulation software, which needs accurate input data.

To study the scintillation properties of C_2F_6, a campaign of both quantum chemistry calculations and dedicated measurements is ongoing.

The degradation of C_2F_6 molecules in the presence of high radiation flux occurs mainly via three processes: ionization, electron abstraction and excitation. The primary degradation

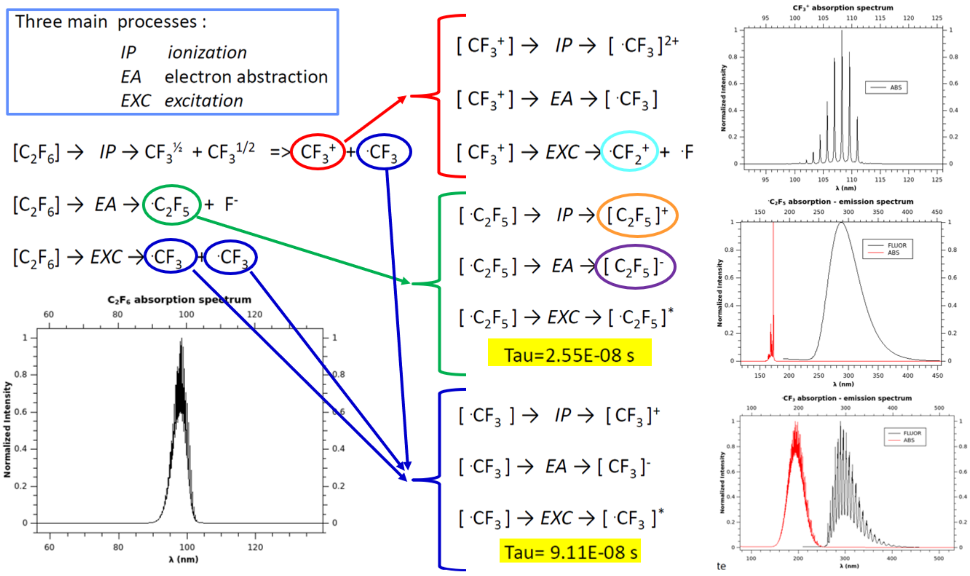

Figure 3: Scheme of the degradation of C_2F_6 molecules

products are: CF_3^+, $\bullet CF_3$, $\bullet C_2F_5$ and F^-, followed by several secondary and tertiary products. We are performing a complete calculation using Quantum Chemistry software.

Fig. 3 schematically presents the main contributions to the degradation process and the photon absorption and emission spectra of the primary degradation products. The radicals $\bullet C_2F_5$ and $\bullet F_3$ present a maximum of the emission around 300 nm.

A measurement of C_2F_6 scintillation has been performed at the CERN-EP-GDD Laboratory, together with the measurement of CF_4 and C_4F_{10} scintillation: the preliminary results are shown in Fig. 4. The main broad peak around 300 nm is particularly evident in all cases, and is about 20 times more intense for the CF_4 gas than for C_2F_6.

3. The dRICH gas circulation system

The dRICH gas circulation system is designed to ensure safe and stable operation of the RICH detector during all phases of operation. Its primary function is to control the internal vessel pressure by maintaining a small and constant overpressure with respect to the surrounding environment (of order 1–3.5 mbar) through dynamic regulation, thereby minimizing mechanical stress on the vessel. A properly dimensioned safety bubbler will ensure passive protection of the large fused-silica windows against dangerous pressure imbalances. A schematic of the dRICH gas system structure is presented in Fig. 5.

The gas system also provides continuous gas purification, with particular emphasis on the removal of oxygen and water vapor contaminants, and guarantees temperature and gas composition homogeneity throughout the vessel volume.

In addition, the circulation system supports operational transitions by enabling vessel filling prior to data-taking periods and efficient gas recovery at the end of data acquisition. During extended shutdowns, the vessel is flushed and maintained with a stand-by gas. While nitrogen

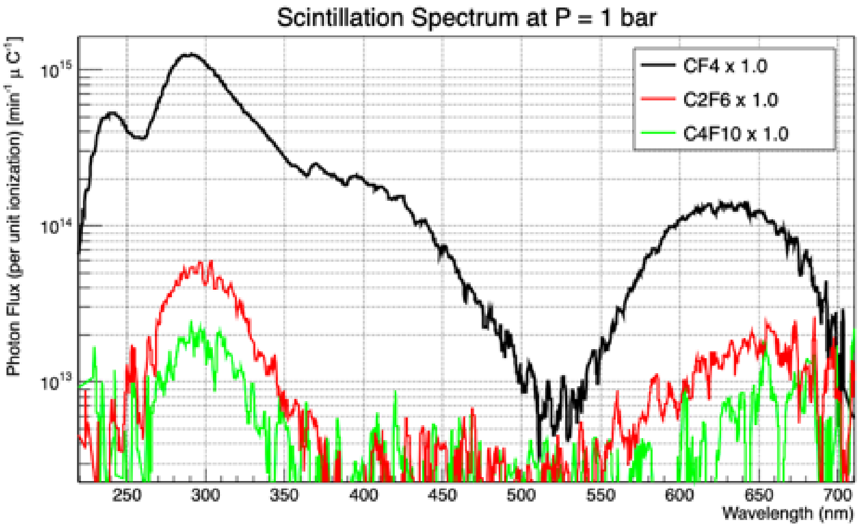

Figure 4: Comparison of scintillation emission spectra from CF_4, C_2F_6 and C_4F_{10}

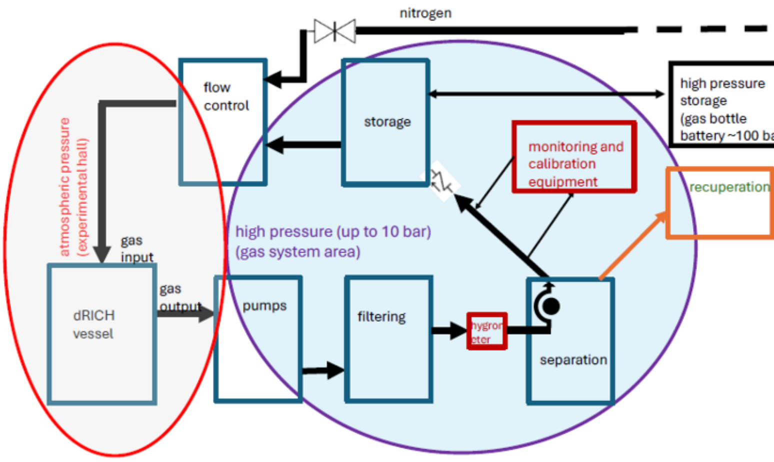

Figure 5: Schematic of the dRICH gas circulation system.

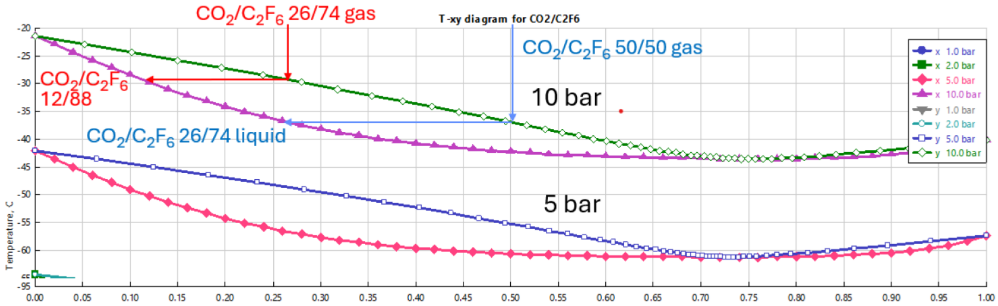

Figure 6: Temperature-composition phase diagram for CO_2/C_2F_6 mixture.

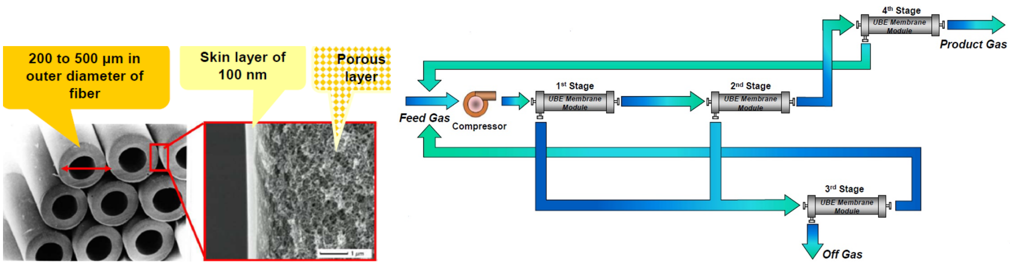

Figure 7: (Left) BPDA-based polyimide hollow fibers (UBE Corporation brochure). (Right) Separator scheme using hollow fibers membranes in a 4-stages configuration (UBE Corporation brochure).

would be the most straightforward choice, high efficiency separation of C_2F_6 from N_2 is technically challenging. For comparison, the commonly used radiator gas C_4F_{10} has a vapor pressure of $\approx$ 200 hPa at -36°C, such that a separator operating at 0.7 MPa can effectively purge $\approx 97\% N_2$ and $3\% C_4F_{10}$. Comparable separation performance with C_2F_6 would require operating at temperatures lower than -100°C.

Phase separation by liquefying the stand-by gas instead of the radiator gas has been investigated, with carbon dioxide in place of N_2. The CO_2/C_2F_6 binary mixture exhibits an azeotropic behavior [7], which limits the effectiveness of distillation-based separation. A study performed by the CERN EP-DT-FS Gas team provided indication in favor of a possible multistep separation approach (distillation column). In Fig. 6 the temperature-composition phase diagram for CO_2/C_2F_6 mixture is presented with an example of possible progressive multistep C_2F_6 enrichment in a separation system operating at 1 MPa.

The proposed solution for the dRICH gas system is a CO_2 separator based on hollow-fiber membrane technology (see Fig. 7, Left). Hollow fibers have a very high surface-to-volume ratio, short diffusion paths, and good mechanical strength when bundled together; BPDA-based polyimide hollow-fiber membranes are expected to provide a favorable balance between permeability and selectivity, high mechanical strength, thermal stability, chemical resistance, and long operational lifetime. The compressed CO_2/C_2F_62 gas mixture will be fed into the hollow fibers, where the higher membrane permeability component, CO_2, will preferentially permeate through the membrane, while the lower-permeability specie, C_2F_6, will be retained. This should result in the production of highly purified (>99%) C_2F_6 at the separator outlet when using a 4-stages membrane configuration as illustrated in Fig. 7 BPDA-based polyimide hollow-fiber membranes

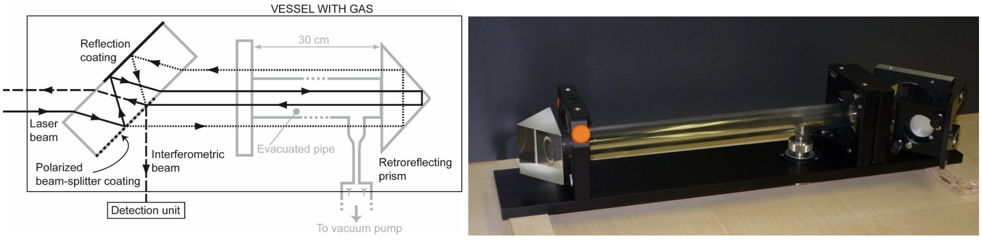

Figure 8: (Left) Scheme of the modified Jamin interferometer. (Right) Picture of the interferometer core element.

are expected to provide a favorable balance between permeability and selectivity, high mechanical strength, thermal stability, chemical resistance, and long operational lifetime.

The separator output gas (mainly standby gas with some fraction of C_2F_6) will be stored in dedicated bottles at high pressure for reuse or proper disposal.

C_2F_6 has a very high global warming potential, with GWP(100) = 12400 according to EU Regulation 2024/573. This makes its use particularly critical from an environmental and regulatory perspective. Fluorinated gases are intensively used in a wide range of industrial sectors, including refrigeration, power distribution, automotive, medical, and semiconductor applications, where in some cases they are practically irreplaceable. Nevertheless, severe regulatory restrictions or even a future ban cannot be excluded.

In this context, ePIC adopts a strictly eco-friendly approach to the use of hexafluoroethane, based on zero emissions for gas pre-cleaning (through the procurement of clean gas), minimization of operational leaks via high-tightness vessels and high-quality gas system components, avoidance of venting of radiator gas after measurements, minimal purging of fluorocarbons trapped in oxy- and hydro-filters, and the development of a fully closed filling and recovery loop, for which dedicated R&D activities are ongoing, in contact with other interested groups, within DRD4 and DRD1 Collaborations at CERN.

Alternatives to C_2F_6 are considered for ePIC dRICH in case of procurement or regulatory restrictions, including different radiator gases (or gas mixtures), with lower environmental impact, and also a pressurized option (Ar at 0.3 MPa, for instance). A dedicated setup for comparative performance studies with test beams has been prepared and will be used in the incoming months.

4. The dRICH gas monitoring

The dRICH gas system will be equipped with dedicated monitoring instrumentation, including an oximeter; a spectrophotometer for continuous monitoring of gas transparency; an interferometer providing real-time refractive-index measurements, combined with temperature and pressure sensors to enable quasi–real-time data processing; and a sonar system to measure the fraction of standby gas in the radiator mixture, particularly during filling and gas recovery operations. Among these instruents, the most original is the modified folded Jamin interferometer (see Fig. 8) that was designed, constructed, and experimentally validated in a collaboration between the Technical University of Liberec and the INFN - Sezione di Trieste.

An incoming He–Ne laser beam (λ = 633 nm) is split by a polarization-sensitive partial beam-splitter coating deposited on the second surface of a plane-parallel plate. One of the resulting beams is reflected by a high-reflectance coating on the first surface, producing two parallel beams of equal intensity with orthogonal polarizations. The first beam propagates through an evacuated,

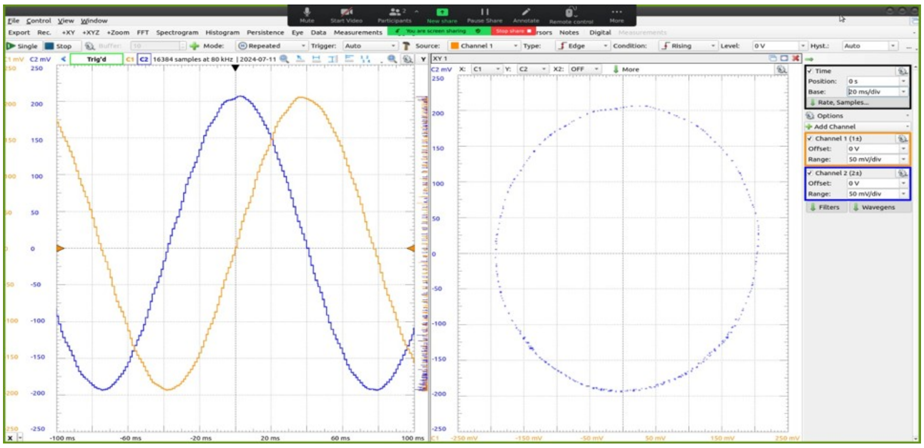

Figure 9: The amplitudes of the two sensors of the interferometer quadrature detection unit.

sealed fused-silica tube, while the second beam travels outside the tube. Both beams are reflected by a retro-reflective 90° prism and subsequently pass through the same fused-silica window at the end of the tube. As a result, the measured phase difference between the beams is induced solely by the refractive-index difference, with contributions from thermal expansion, mechanical stress, and other systematic effects effectively suppressed.

The interferometer is equipped with a quadrature detection unit. The detection system employs two sensors sensitive to orthogonal polarizations, phase-shifted by $\pi/2$ with respect to each other and providing a voltage output. The measurement of a one-fringe displacement (equivalent to a 2π phase shift) corresponds to a refractive-index variation of 10^{-6}. as can be seen in Fig. 9. A sensitivity better than 10 ppb can be achieved in refractive index monitoring.

5. Conclusion

Hexafluoroethane has been identified as the preferred radiator gas for the ePIC dRICH detector.

The optical and chemical properties of C_2F_6 are being investigated through quantum-chemistry calculations and dedicated measurements.

The design and prototyping of the ePIC dRICH radiator gas system is progressing, successfully facing the challenges related to the implementation of an eco-friendly gas system. A test-beam campaign employing a pressurized radiator gas setup is ongoing to provide risk mitigation.

Different options for separating radiator and stand-by gas are under investigation; selective-permeability membranes represent the most promising solution for the gas separation.

Dedicated radiator-gas monitoring tools are being developed, including a modified Jamin interferometer providing high-precision refractive-index variation measurement.

The perspectives to achieve the ambitious goals of ePIC dRICH seem promising.

6. Acknowledgment

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