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Full Length Article

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 be 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. Selective-permeability membranes, rather than distillation, are identified as the preferred option for separating the radiator gas from other gas components.

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.

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

1. Introduction

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

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 features a compact design combining a SiO_2 aerogel radiator (≈2.5 m^2) with a hexafluoroethane (C_2F_6) gas radiator (≈12 m^3). The refractive indices are 1.026 and 1.008, respectively. An array of spherical mirrors, divided into six sectors, focuses the Cherenkov light onto photon detectors [3] based on SiPMs, arranged on a curved surface and operated at low temperature (≈−40 °C).

The high granularity of the SiPM-based photon detectors, together with the low chromaticity of C_2F_6, are key elements in achieving the challenging high-momentum hadron-identification goals of ePIC.

The properties of hexafluoroethane have been investigated and compared to those of the commonly used perfluorobutane (C_4F_{10}) radiator gas. Simulations show that, despite the significantly lower average number of expected photons per ring (about 60% of that expected for C_4F_{10}) and a comparable ring angle resolution, C_2F_6 provides increased π-K discrimination power in the momentum range of interest, up to 50

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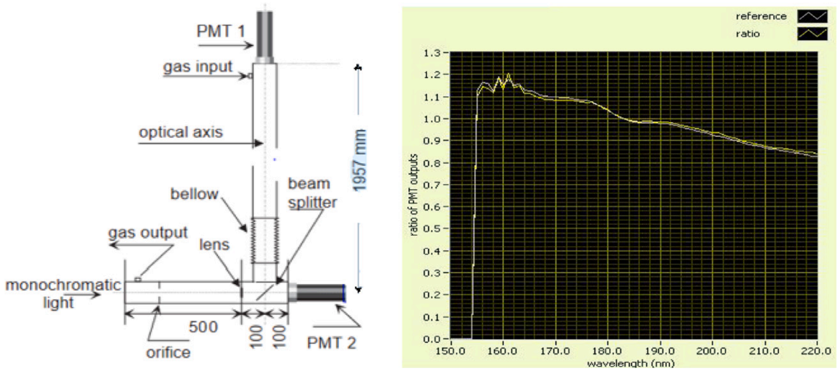

Fig. 1. (Left) Scheme of the COMPASS/AMBER RICH transparency measurement device: a light beam from a monchromator is split between a direct and a ≈ 2 m long absorption column, both ending with a PMT. (Right) The ratio of the currents of the two PMTs is plotted versus wavelength: in white the reference curve (N_2), in yellow the C_2F_6 absorption measurement curve. The transparency exceeds 98% over the whole measured range.

GeV/c, owing to an approximately 30% larger π–K Cherenkov angle separation.

The use of the less commonly employed C_2F_6 as radiator gas introduces challenges that require dedicated studies and innovative solutions. Stringent requirements on the dRICH gas system arise from the difficulty of separating C_2F_6 from neutral gases and from its high global warming potential, motivating efforts to minimize the environmental impact. Selective-permeability membranes are therefore considered the default option for gas separation, as distillation is particularly challenging for C_2F_6 due to its phase diagram.

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.

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.

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 ($\mathrm{d}n/\mathrm{d}\lambda = 0.2 \times 10^{-6}\ \mathrm{nm}^{-1}$ 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 baseline dRICH SiPMs this corresponds to 300–800 nm, although studies are ongoing on SiPMs with enhanced UV sensitivity.

Transparency measurements have been performed using two systems: for the VUV range, the monochromator setup (see Fig. 1) of the COMPASS/AMBER RICH at CERN; for the 200–900 nm wavelength range, a commercial spectrophotometer (PerkinElmer® LAMBDA 850+) equipped with a 20 cm long cell with fused-silica windows, rated for a pressure up to 1 MPa (see Fig. 2). The measured transparency of C_2F_6, corresponding to a 2 m path at 0.1 MPa, exceeded 98% at all wavelengths, even for gas stored in bottles for long time (≈4 years).

The spectrophotometer system 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 potential concern for its use in an environment characterized by intense ionizing radiation. The impact of scintillation-induced photon background on the expected dRICH resolution is studied using simulation tools that require accurate input data.

To study the scintillation properties of C_2F_6, a combined program of calculations and dedicated measurements is currently underway.

The degradation of C_2F_6 molecules under high radiation flux occurs mainly via three processes: ionization, electron abstraction and excitation. The primary degradation products are: CF_3^+, $\bullet CF_3$, $\bullet C_2F_5$ and F^-, followed by several secondary and tertiary species. A comprehensive quantum-chemistry calculation is being performed to model these processes.

Fig. 3 schematically presents degradation pathways, together with the photon absorption and emission spectra of the primary degradation products. The radicals $\bullet C_2F_5$ and $\bullet CF_3$ exhibit emission maxima 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. Preliminary results, shown in Fig. 4, reveal the expected main broad peak around 300 nm in all cases, with the scintillation intensity of C_2F_6 being about 20 times lower than that of CF_4.

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. Its primary function is to control the internal vessel pressure by maintaining a small, constant overpressure with respect to the environment (of order 1–3 hPa) through dynamic regulation, thereby minimizing mechanical stress. 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 shown in Fig. 5.

The gas system also provides continuous gas purification, by oxygen and water vapor removal, and ensures temperature and gas composition homogeneity throughout the vessel volume.

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 would be the simplest choice, efficient separation of C_2F_6 from N_2 is technically challenging. For comparison, the commonly used radiator gas C_4F_{10}, with a vapor pressure of ≈200 hPa at −36 °C, allows effective separation at 0.7 MPa, purging ≈97% N_2 and 3% C_4F_{10}. Achieving comparable performance with C_2F_6 would require temperatures below −100 °C.

Phase separation by liquefying the stand-by gas has therefore been investigated, using CO_2 instead of N_2. The CO_2/C_2F_6 mixture exhibits azeotropic behavior [7], limiting the effectiveness of distillation. A study performed at CERN nevertheless indicates that a multistep distillation approach (or a distillation column) may be feasible. In Fig. 6

Fig. 2. Setup for the measurement (and monitoring during ePIC dRICH operation) of the C_2F_6 transparency in the 200–900 nm wavelength range.

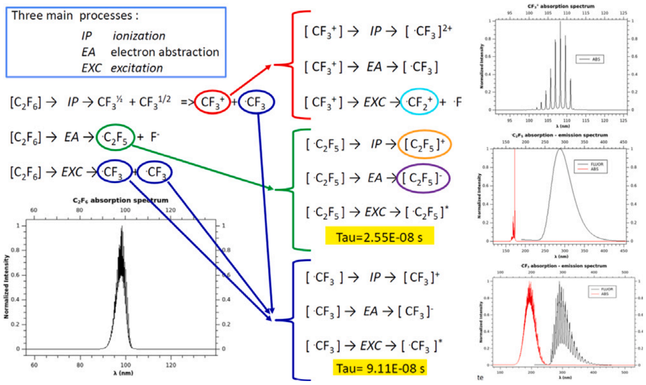

Fig. 3. Scheme of the degradation of C_2F_6 molecules.

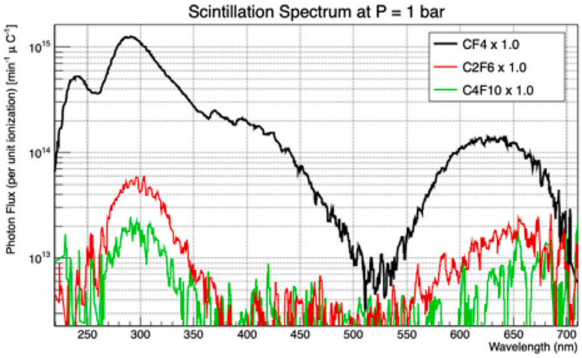

Fig. 4. Comparison of scintillation emission spectra from CF_4, C_2F_6 and C_4F_{10}.

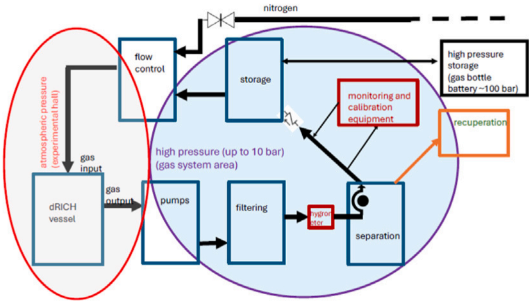

Fig. 5. Schematic of the dRICH gas circulation system.

the temperature-composition phase diagram for CO_2/C_2F_6 mixture is presented with an example of progressive C_2F_6 enrichment at 1 MPa.

The proposed solution for the dRICH gas system is a CO_2 separator based on hollow-fiber membrane technology (Fig. 7, Left). Hollow fibers offer high surface-to-volume ratio, short diffusion paths, and good mechanical robustness when bundled together; commercial BPDA-based polyimide hollow-fiber membranes (UBE Industries Ltd., Japan) provide a favorable balance of permeability and selectivity, as well as high thermal and chemical stability, enabling long operational lifetimes. When a CO_2/C_2F_6 gas mixture is fed into the hollow fibers, the higher-permeability, CO_2, preferentially passes through the membrane, while the lower-permeability, C_2F_6, is retained. This process should produce highly purified (>99%) C_2F_6 at the separator outlet when using a 4-stages membrane configuration as illustrated in Fig. 7.

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 ($GWP_{100} = 12400$ according to EU Regulation 2024/573), making its use critical from an environmental and regulatory perspective. Fluorinated gases are widely used across industrial sectors for refrigeration, power distribution, automotive, medical, and semiconductor applications, and 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 C_2F_6 use, including zero emissions gas pre-cleaning, minimization of operational leaks via high-tightness vessels and high-quality gas system components, avoidance of radiator gas venting, minimal purging of fluorocarbons from oxy- and hydro-filters, and the development of a fully closed filling and recovery loop. Dedicated R&D for this system is 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), 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 instruments, including an oxymeter, a spectrophotometer for continuous gas transparency measurement, an interferometer for real-time refractive-index mmonitoring, combined with temperature and pressure sensors, and a sonar system to track the fraction of standby gas in the radiator mixture, particularly during filling and recovery operations.

Among these instruments, the most original is the modified folded Jamin interferometer (see Fig. 8), designed, constructed, and experimentally validated through a collaboration between the Technical University of Liberec and the Trieste Section of INFN.

In the prototype Jamin interferometer a 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 resulting beam is reflected by a high-reflectance coating on the first surface, so that two parallel beams of equal intensity, with orthogonal polarizations, are produced. The first beam propagates through an evacuated, sealed fused-silica tube, while the second beam travels outside the

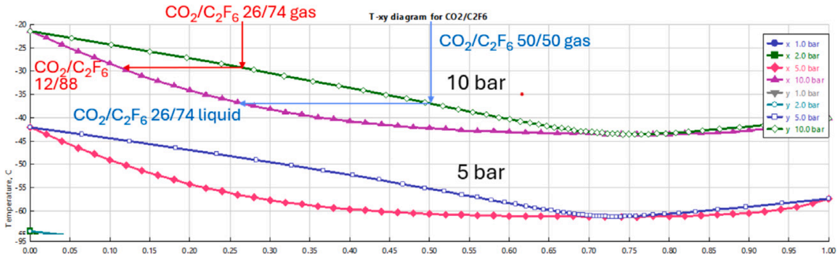

Fig. 6. Temperature-composition phase diagram for CO_2/C_2F_6 mixture.

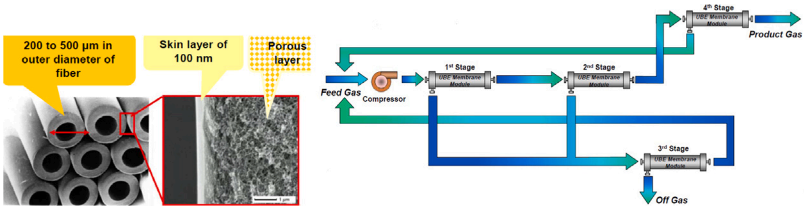

Fig. 7. (Left) BPDA-based polyimide hollow fibers (from UBE Corporation brochure). (Right) Schematic of a 4-stage hollow-fiber membrane gas separator using the same fibers (from UBE Corporation brochure).

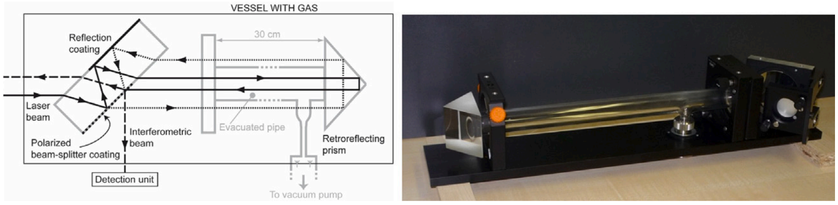

Fig. 8. (Left) Scheme of the modified Jamin interferometer. (Right) Picture of the interferometer core element.

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. A one-fringe displacement (2π phase shift) corresponds to a refractive-index variation of 10^{-6}, since the optical path corresponds to $\approx 10^6\ \lambda$.

Fig. 9 shows the sensors signals for a refractive index variation corresponding to approximately one-fringe displacement, illustrating the high sub-fringe resolution. The prototype Jamin interferometer achieves sensitivity of ≈10 ppb, well below the 1 ppm resolution required for dRICH performance in ePIC.

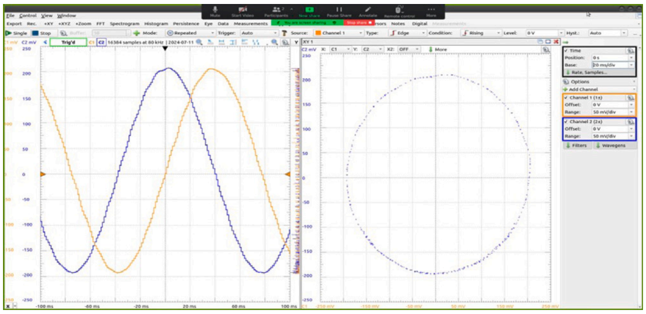

Fig. 9. Signals from the two sensors of the interferometer quadrature detection unit, shown as a function of time and in the x–y display mode.

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 characterized through quantum-chemistry calculations and dedicated measurements.

The design and prototyping of the ePIC dRICH radiator gas system are progressing successfully, addressing the challenges associated with implementing an eco-friendly gas system. A test-beam campaign with a pressurized radiator gas setup is ongoing to support risk mitigation.

Various approaches for separating radiator and stand-by gas are under investigation, with selective-permeability membranes emerging as the most promising solution.

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

Overall, the prospects for achieving the ambitious performance goals of the ePIC dRICH are promising.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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