AEROGEL AND ITS APPLICATIONS TO RICH DETECTORS

E. Nappi
INFN, Sez. Bari, Istituto Nazionale di Fisica Nucleare, via Amendola 173, I-70126 Bari, Italy

ABSTRACT

Beam test results show that the “new generation” aerogel has attractive features and appears an interesting candidate as radiator in Ring Imaging Cherenkov (RICH) detectors. The challenging applications envisaged in the LHCb experiment at CERN and in the HERMES experiment at DESY will be reviewed.

1 Introduction

The hadron identification in the momentum domain of few GeV/c represents a challenge for Cherenkov detectors, in fact traditional gas and liquid radiators have a refractive index either smaller of 1.0018 (C_5F_{12}) or larger than 1.27 (liquid C_6F_{14}). To avoid the use of gases at high pressure or in unmanageable liquified form, the only possible way to partially close the gap in refractive indices is represented by silica aerogel that can be produced in a fairly wide range from $n = 1.004$ to $n = 1.1$. After the unsuccesful attempt of Linney and Peters [1] in 1972 to use compressed silica powder to obtain a material with n<1.2, soon abandoned due to the very poor transparency of their radiators, in 1973 Cantin *et al.* [2] adopted silica aerogel in Cherenkov counters. Although aerogel was discovered in 1931 [3], a time and cost effective fabrication method was found only in the late 1970s, when France decided to store rocket fuels in porous materials. Since then, an explosive growth of specific application in the scientific community has stimulated new techniques for the production of aerogel with remarkable optical quality. Indeed aerogel is now currently produced in a sol-gel chemical process that provides a very transparent hydrophobic polymer gel structure while old aerogel was fabricated in a way to lead to seedy hydrophillic colloidal structures. The “breakthrough” in aerogel fabrication promoted more advances in the use of this material in Cherenkov detectors, as V.I. Vorobionov [4] and H. v. Hecke [5] pointed out in 1991 and 1993, respectively. Nonetheless, the major merit of the rapid progress of aerogel in real RICH devices must be ascribed to J. Seguinot and T. Ypsilantis, who revised the van Hecke proposal in the light of currently available photodetector technology and envisaged an appealing application in the LHCb experiment [6]. The outstanding potential of their detector design inspired the upgrade of HERMES at DESY [7].

In the next section, the chemical and physical properties of silica aerogel will be briefly reviewed, results from beam tests at CERN-PS are then presented in Sec. 3. An outlook of the experiments LHCb and HERMES will be given in Secs. 4 and 5, respectively. Finally, Sec. 6 is devoted to conclusions.

2 Chemical and Physical Properties of Silica Aerogel

Aerogel is a manmade material that could have a density as low as three times that of air. It essentially consists of grains of amorphous SiO_2 with sizes ranging from 1 to 10 nm linked together in a three-dimensional structure filled by trapped air. The huge number of such tiny primary particles determines an internal surface close to 1000 m^2/g that plays the fundamental role in the aerogel chemical and physical behavior. It exists a simple relationship between the resultant index of refraction and the aerogel density ρ in g/cm^3 [8]:

$$n = 1 + 0.21\ \rho. \tag{1}$$

Density values lying between 0.003 g/cm^3 and 0.55 g/cm^3 are in principle available, corresponding to refractive indices of n=1.0006 ($\gamma_{threshold} = 29$) and n=1.11 ($\gamma_{threshold} = 2.3$), respectively.

In the aerogel preparation, the starting phase is the hydrolysis and condensation of silicon alkoxides in presence of an alcoholic solvent. Aerogel is then obtained by removing the solvent in a quite complicated way because if the liquid were simply left to evaporate, then adhesion and capillary forces would shrink the gel into a very dense material. Therefore, in order to prevent the collapse of the porous structure, the pressures and temperatures during liquid extraction must be raised above the triple point of the solvent. In the past, this operation required high temperatures and high pressures. Moreover, the demanding control of the correct quantity of solvent made possible only the production of silica aerogel within a limited range of refractive indices [8].

In the final treatment, the aerogel needed to be baked at several hundred degrees Celsius in order to dry off the residual adsorbed solvent. The final product had surfaces not particularly clean and flat and the baking treatment makes it very hydrophillic, consequently aerogel samples used in the experiments had to be often rebaked during their operative life.

In 1988, a new fabrication process was developed at Lawrence Livermore National Laboratory, later on adopted by the russian team lead by A. P. Onuchin in collaboration with the Boreskov Institute of Catalysis in Novosibirsk to produce very transparent silica aerogel with refractive index in the range 1.005–1.055 [9].

Oppositely to the aforementioned method, called “one-step,” the new one treats the starting gel into two succesive steps: the alcohol (mainly methanol) within the gel is, in the first step, replaced by liquid

CO_2 that undergoes a supercritical drying in the second step without damaging the aerogel [10]. The “two-step” process is much safer than the simply extraction of supercritical methanol, in fact CO_2 has a lower critical point (31^oC and 1050 psi) than methanol (240^oC and 1600 psi) and does not pose an explosion hazard as alcohol does.

But the breakthrough in the fabrication process occured only few years ago, in the framework of the Belle experiment at the B-factory in Japan, when silica aerogel with very low refractive index was produced by means of a revolutionary technique [11]. The National Laboratory for High Energy Physics (KEK) in Japan in collaboration with Matsushita Electric Works developed a method based on the old single-step process but adopting the basic philosophy of the two-step method. The aerogel is baked under supercritical conditions after replacing the alcohol with CO_2 by avoiding in this way the complication of the alcohol distillation. This aerogel is hydrophobic, due to a treatment of the surface of the aerogel pores, and highly transparent, but it loses this property if a baking process is applied to improve its transmittance.

Moreover, KEK aerogel has been found to be radiation hard at least up to 9.8 mrad of gamma ray dose [12].

2.1 Optical Properties

The granular structure of aerogel with a typical length scale of few nm determines its optical properties. Indeed, the behavior of visible light in aerogel is dominated by Rayleigh scattering which increases as the fourth power of the frequency. The bluish haze that surrounds aerogel samples is an effect of the Rayleigh scattering since short wavelengths are the most severely affected by the continuos scattering mechanism. The internal absorption does not play a significant role in the visible region (the intensity drops to 1/e only after several cm), while weak absorbances appear in the infrared. The measured transmittance t of an aerogel sample of thickness L, as function of the light wavelength λ in the range from 300 nm to 700 nm, is fairly fitted by the expression:

$$t = Ae^{-CL/\lambda^4}, \tag{2}$$

where C characterizes the aerogel clarity, and A is the measured transmission in the long-wavelength region. Samples with a good optical quality have A and C close to the value of 1 and 0 respectively. The typical values of the parameters A and C have been reported in Table 1 where samples with $n = 1.03$ produced with the aforementioned fabrication methods are compared.

When the Rayleigh scattering occurs, the directionality of the Cherenkov radiation is completely lost. Therefore, the major concern associated with the design and construction of a RICH detector with an aerogel radiator is whether the Cherenkov photons that traverse the aerogel without any scattering are in sufficient number to allow the measurement of their emission angle with the expected accuracy.

Table 1: Silica aerogel optical parameters

Fabrication method	Producer	A	C (μm^{4}cm^{-1})	Ref.
“One-Step”	Airglass Co. (Sweden)	0.96	0.018	[13]
“Two-Step”	Jet Propulsion Lab (USA)	0.96	0.012	[6]
“Two-Step”	Boreskov Institute of Catalysis (Russia)	0.96	0.005	[14]
“KEK Method”	KEK Lab. (Japan)	0.96	0.0085	[15]

The fraction N of photons of wavelength λ that cross undeflected an aerogel sample of thickness L, characterized by the optical parameters A and C, is given by:

$$N = A\lambda^4(1 - e^{-CL/\lambda^4})/CL. \tag{3}$$

Although the C parameter of Russian samples is smaller than that of aerogel samples fabricated with other methods, the KEK aerogel has the big advantage to be hydrophobic and therefore it ages less in the long term. By assuming the best optical parameters, the fraction of photons of 350 nm that have not undergone any scattering inside a 3 cm thick sample is about 60%, but N raises up to almost 85% for photons of 500 nm.

These simple calculations show that the useful production of Cherenkov light is limited to the visible. This therefore places high demands on photon detection. A large area multicell hybrid photodiode (HPD) with a bialkali photocathode seems the most promising candidate to detect and resolve single photoelectrons from aerogel [6]. Moreover, HPDs ensure operational stability on a long term since they are devices without intrinsic gain [16].

3 Beam Test Results

In the framework of Hermes and LHCb RICH detector development, investigations have been carried out to prove the feasibility of detecting a single event Cherenkov ring produced in aerogel [17].

Aerogel samples with n=1.03, procured from KEK, were tested at the PS-T9 beam facility at CERN with 10 GeV/c negative pions.

The experimental setup is schematically shown in Fig. 1. It consists of a black painted light-tight aluminum box flushed with nitrogen at atmospheric pressure, which contains the aerogel sample and an angled spherical mirror used to focalize the light from the radiator on the photodetector entrance window. The mirror has a focal length of 45 cm, and thus, aerogel rings with a diameter d of 11 cm are expected in the mirror focal plane. Smaller rings, with $d \sim 2$ cm, are instead produced by particles in nitrogen between the aerogel and the mirror. Two different systems employing either a single phototube (PM) or a matrix of 114 phototubes have been used to detect the emitted light.

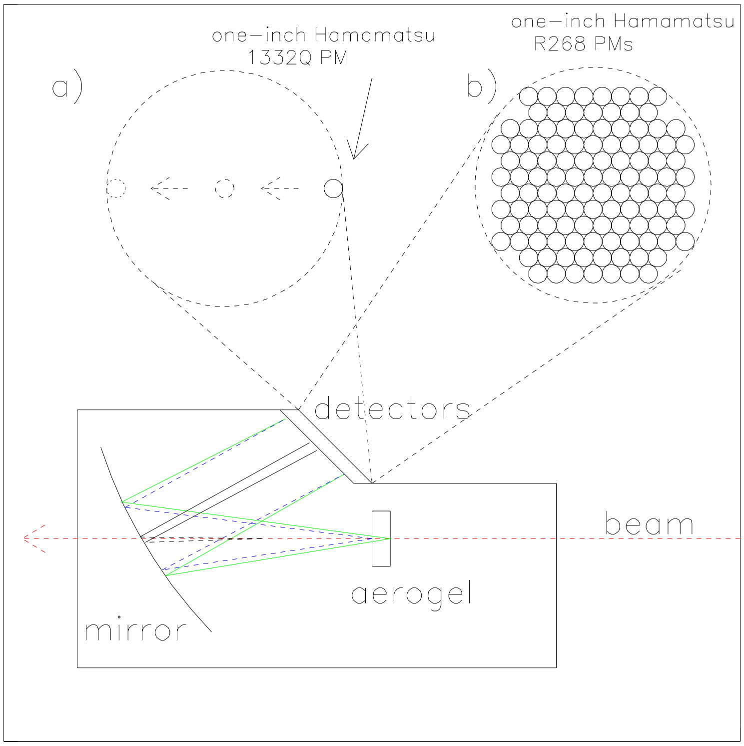

Figure 1: Schematic layout of the test setup at CERN for the imaging of the Cherenkov light produced in silica aerogels with n=1.03. Two detector schemes were consecutively implemented on the mirror focal plane: (a) a single phototube mounted on a motorized stage, and (b) an array of 114 photomultipliers.

In the first part of the test, a Hamamatsu 1332Q PM with a bialkali photocathode of one inch was installed on a linear motorized translator in order to scan horizontally across the mirror focal plane. The number of counts, referred to the same number of triggers, registered by the PM during the scanning of the focal plane, is reported in Fig. 2 as a function of the position. In order to suppress the noise and mantain sensitivity to single photoelectrons, a threshold in the pulse height was placed between the pedestal and the one-photoelectron ($p.e.$) peak of the PM spectrum. The stronger peak in Fig. 2, obtained with the PM nearly in the center of the focal plane, corresponds to the Cherenkov ring produced in nitrogen. Another peak is clearly visible when the PM is displaced 11.6 cm from the position of the maximum of the first peak. The same enhancement is seen moving the PM in the opposite direction. These enhancements are originated from the unscattered Cherenkov light produced in the radiator and prove that KEK aerogel preserves the direction of an appreciable fraction of Cherenkov photons. From the values of the mirror focal length and from the observed radius of the aerogel ring, a refractive index of 1.03 has been calculated, in good agreement with the nominal value provided by the KEK group (n=1.028). The resolution of the peaks in Fig. 2 is dominated by the size of the PM photocathode.

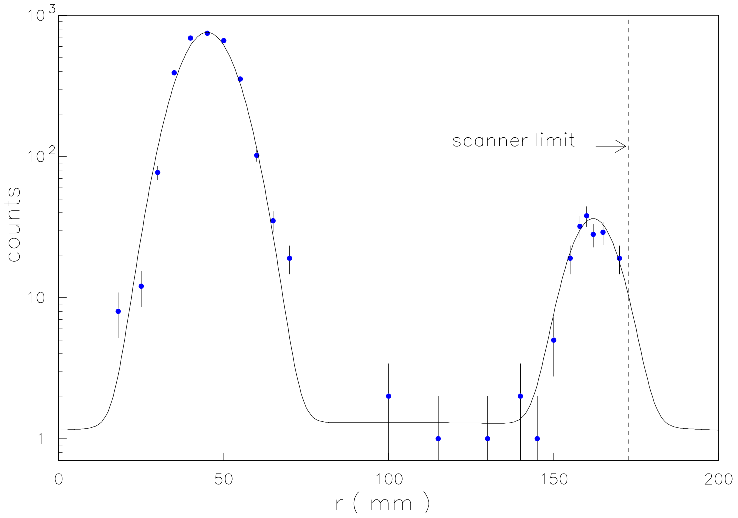

Figure 2: Scan with one PM across the mirror focal plane. The first peak, on the left-hand side, is due to the unresolved Cherenkov ring from nitrogen, while the second peak corresponds to Cherenkov photons produced in the aerogel. The counts between the two peaks are very few as expected.

In the second part of the test, the array of 114 one-inch PM's allowed to perform the electronic imaging of the full Cherenkov pattern. A threshold was applied to the signal of each of the 114 PM's recorded, corresponding to about 2σ of the pedestal distribution.
In Fig. 3, the PM hit map containing a large number of overlapped events is reported. The nitrogen and aerogel rings are clearly visible over a very low background.

From the positions and the number of PM's fired in each event, the average radius of the ring, the average number of Cherenkov photoelectrons per ring and the average background due to photons emerging from the aerogel after having undergone one or more scatterings, were calculated [17]. The following results, referred to a 2.5 cm thick sample, were found:
(1) a ring radius value of 11.4 ± 0.5 cm;
(2) an average number of 14.9 $p.e.$ per ring; and
(3) an average background of 2.4 $p.e.$ per ring.

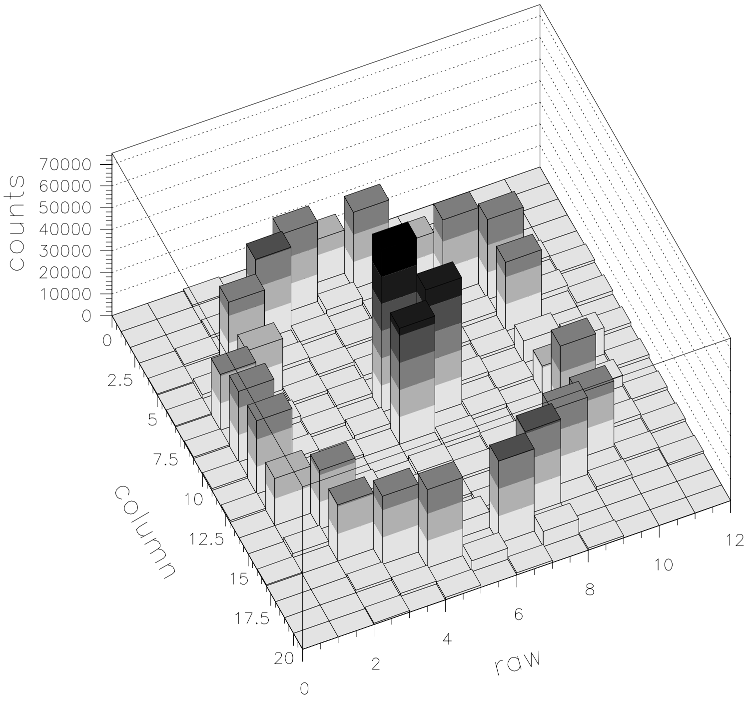

Figure 3: The photomultiplier hit map over the mirror focal plane obtained by overlapping events from a full run. The Cherenkov ring from aerogel is clearly visible, while the ring from nitrogen is poorly resolved by the three central photomultipliers. The sparse background hits show the good optical quality of the tested aerogel sample.

4 THE LHCb EXPERIMENT AT CERN

LHCb is an experiment designed to study CP violation in B decays. It is conceived as a collider-mode forward spectrometer which will be operational at the LHC start-up. The proposed layout (Fig. 4) features an accurate momentum reconstruction and particle identification since precision determination of the CKM unitarity triangle angles requires an excellent pion/kaon separation over the momentum range from 1 GeV/c to 150 GeV/c. A detailed description of LHCb can be found in Ref. [18], in the following only those aspects of the setup which concern particle identification will be addressed.

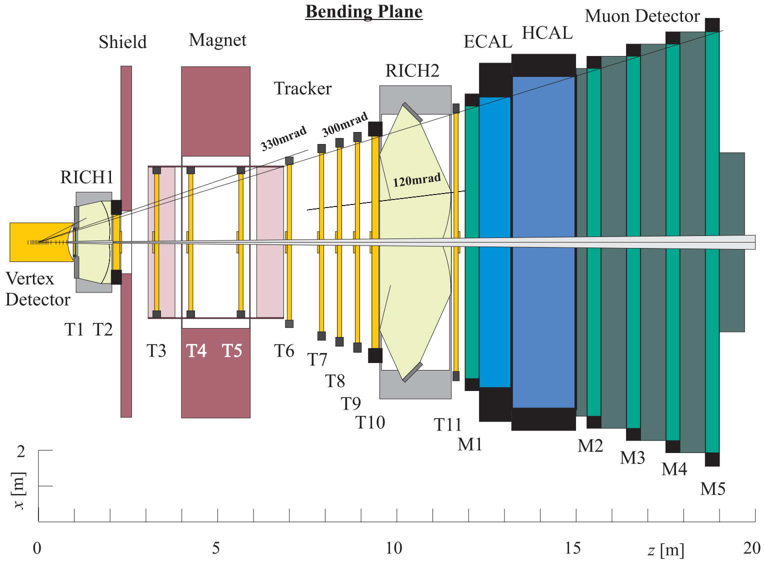

Figure 4: LHCb layout.

The desired momentum range for pion/kaon separation cannot be spanned by one refractive index setting; therefore, two focused RICH detectors with three radiators have been proposed. The first RICH is placed upstream the dipole magnet to allow the identification of particles in the low momentum region from 1 to 60 GeV/c. It is based on the innovative idea to implement aerogel and C_4F_{10} radiators in the same focusing system by positioning the aerogel radiator close to the gas vessel entrance window and tilting the 2 m focal length mirror to bring the image out of the beam aperture in order to reduce secondary interactions. Photons are detected via an array of HPDs located on each side of the RICH detector (Fig. 5). The second RICH has a 2 m long CF_4 gas radiator to identify high momentum particles between 16 and 150 GeV/c. A system of mirrors transfers the ring images to the HPD array located in such a way that it is not traversed by particles.

Anticipated performances of the RICH systems are listed in Table 2. The particle identification layout

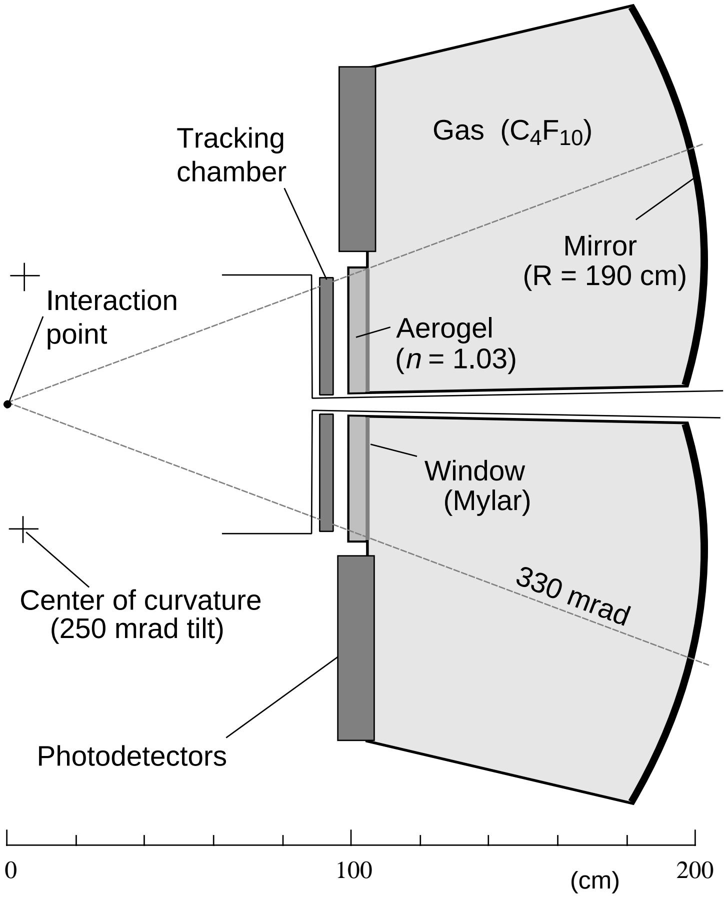

Figure 5: The innovative set-up of the LHCb RICH with aerogel and gas radiators.

proposed has a high discrimination power, but the innovative technical solution envisaged need crucial tests to determine their feasibility.

5 The HERMES Experiment at DESY

Hermes is an internal gas-target experiment designed to investigate the nucleon spin structure functions at HERA [19]. An open spectrometer has been built with the aim to measure the scattered electron and the leading hadrons coming from the target fragmentation with a momentum and angle resolution of 1% and 1 mrad (at 4 GeV/c), respectively.

Table 2: Expected performances of LHCb RICH detectors with n=1.03 aerogel radiator and CF_4, C_4F_{10} gas radiators. The following factors are listed: momentum thresholds for pions and kaons, maximum Cherenkov emission angle, contributions to the angle resolution from the uncertainty of the photon emission-point, from the radiator chromatic dispersion and from photon detector spatial resolution (assuming 2.5x2.5 mm^2 pixel size), total angle resolution per photoelectron, and the momentum upper limit of $3\sigma_{\pi/K}$ separation.

n	1.03 (aerogel)	1.0005 (CF_4)	1.0014 (C_4F_{10})
$p_{tresh,\pi}$ (GeV/c)	0.6	4.5	2.7
$p_{tresh,K}$ (GeV/c)	2.0	15.6	9.4
θ_C (mrad)	240	30	53
$\sigma_\theta^{emission}$ (mrad)	0.4	0.2	0.6
$\sigma_\theta^{chromatic}$ (mrad)	1.2	0.3	0.6
σ_θ^{pixel} (mrad)	0.7	0.2	0.7
σ_θ^{total} (mrad)	1.5	0.4	1.1
p_{max} (GeV/c)	20	146	73

The spectrometer consists of a conventional dipole magnet of 1.3 Tm and many tracking chambers for an accurate event reconstruction (Fig. 6). The scattered primary electron is identified with an efficiency greater than 97% (with less than 1% of hadron contamination) by the combination of a lead-glass calorimeter, a preshower, and a transition radiation detector. The threshold Cherenkov detector that formerly allowed the identification of pions above a threshold of 3 GeV/c using C_4F_{10} was replaced by a LHCb-like dual radiator RICH during the summer of 1998 [20].

In this way, the unique opportunity to provide valuable information on the flavor dependence of the spin structure functions and estimates of the strange sea polarization is fully exploited by an unambiguous identification of pions, kaons, and protons in the momentum range from 3 to 20 GeV/c.

6 Conclusions

Hydrophobic, crack-free, very transparent aerogel samples are now routinely fabricated. Loss of photons due to the absorption and scattering processes in the bulk material have been minimized by using innovative production techniques. Aerogel ageing effects due to exposure to atmosphere can be alleviated by proper handling and storage. This new silica aerogel can be an ideal medium to be employed in RICH detectors as radiator. Test beam studies of aerogel gave very promising results indicating that KEK-aerogel has the required optical quality, and therefore, it is suitable to be used for RICH detectors. Moreover results show that the background from scattered photons is low.

LHCb and HERMES experiments have already planned to implement an aerogel RICH in their setup. Indeed, a RICH device with aerogel and an array of visible light photodetectors shows an attractive con-

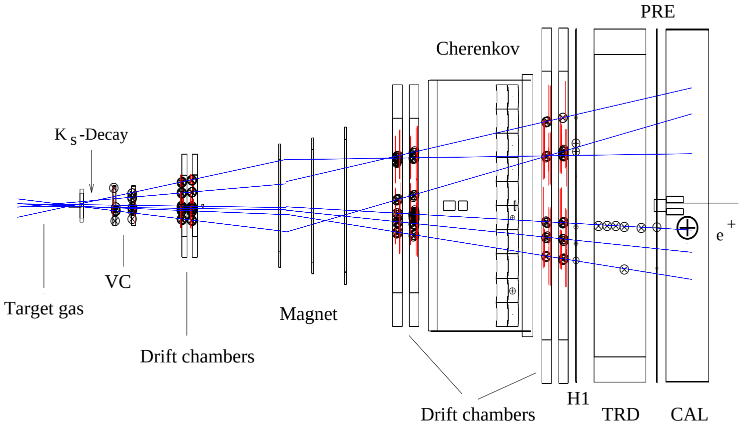

Figure 6: Reconstruction of an event in the HERMES spectrometer. The scattered positron has been recognized by hits in the transition radiation detector (TRD), the preshower counter (PRE) and the electromagnetic calorimeter (CAL).

ceptual simplicity due to the modest service and maintenance needs. The major drawback of this technique is the high detector cost per unit of surface. In fact, the commercial available devices (HPD and multi-anode photomultipliers) have suitable performances but they suffer of large inactive area and high cost. The developments of cheap hybrid phototubes with large active area is underway at CERN in collaboration with INFN-Bari and ISS-Rome [21].

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