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Total absorption Cherenkov spectrometers

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Contents

Abstract. A short review of 50 years of work done with Cherenkov detectors in laboratories at the Lebedev Physical Institute is presented. The report considers some issues concerning the use of Cherenkov total absorption counters based on lead glass and heavy crystals in accelerator experiments.

Keywords: electron beams, Cherenkov radiation, Cherenkov total absorption counters, spatial and energy resolutions

1. Introduction

At the beginning of his postgraduate work in 1932, P A Cherenkov studied on the instructions of his scientific advisor S I Vavilov the luminescence of uranyl salt solutions, and observed the emission of liquids irradiated by γ-rays, which differed in its nature from luminescence [1]. Cherenkov investigated the main properties of the phenomenon he discovered, and these results formed the basis for the explanation of the nature of emission of a substance under the action of charged particles propagating at a superluminal speed in a medium in the theory developed by I E Tamm and I M Frank in 1937 [2].

Soon, Collins and Reiling [3] in the USA observed this phenomenon with a relativistic electron beam and verified the relationship $\cos\varphi = 1/n$. Notice that the authors of this paper [3] coined the term 'Cherenkov radiation', which became generally accepted abroad (in our country, the term 'Vavilov–Cherenkov radiation' is also used). Already at that time, Cherenkov made his proposal to develop Cherenkov counters for detecting charged particles. Of course, this idea seemed then too optimistic. Frank recalled that, together with Cherenkov, he considered in 1934 the possibility of studying cosmic rays by observing the accompanying radiation in the terrestrial atmosphere. However, their estimates showed that the contribution of Cherenkov radiation from cosmic particles to the night sky emission is negligibly small, and only with the advent of commercial photomultipliers did the idea of creating Cherenkov detectors of relativistic particles become real.

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2. Development of total absorption spectrometry

Beginning in the 1950s, when the energy of accelerated particles reached several hundred MeV, researchers at the Lebedev Physical Institute (LPI), RAS started to develop various methods based on the application of the Cherenkov effect for detecting high-energy electrons and photons. In this paper, our attention will be focused on the development of Cherenkov total absorption spectrometers (CTASs), which have been successfully used in many experiments in high-energy physics with accelerators such as C25P (LPI, Troitsk, Moscow region), U-70 (Institute for High-Energy Physics (IHEP), Protvino, Moscow region) and HERA (Hadron-Electron Ring Accelerator (DESY Research Center, Hamburg, Germany). In a number of cases, the choice of an appropriate CTAS was decisive for obtaining the scientific results. The characteristic features of CTASs ensuring their wide application in experiments include:

(i) the high electron and photon detection efficiency, reaching almost 100%;

(ii) possibility of measuring the energy of detected particles. The energy resolution lies in the range from 30% to 2% for energies from 100 MeV to 50 GeV;

(iii) linear dependence of the signal amplitude at the spectrometer output on the energy of detected particles;

(iv) high selectivity in the choice of shower-forming particles;

(v) threshold properties in the detection of nonrelativistic particles;

(vi) considerably smaller size and weight than those of spectrometers of other types for such measurements;

(vii) high aperture ratio of a CTAS virtually coinciding with its entrance aperture. This allows the building of multichannel hodoscopic systems consisting of separate moduli, and

(viii) short Cherenkov radiation pulse duration (on the order of a few nanoseconds) allowing the use of spectrometers in fast electronic circuits and time-selected schemes.

The operation principle of a CTAS can be schematically described as follows. The energy of a detected particle (a photon with energy E_0) is distributed among particles of the shower due to the development of an electromagnetic cascade in a radiator substance. The charged particles (electrons and positrons) of the shower with energies exceeding the radiation threshold in the material of the radiator emit Cherenkov photons. When the required methodical conditions are fulfilled (the absence of shower leakage, uniformity of the light collection over the entire volume of the radiator, linearity of the detection channel, etc.), proportionality is observed in the chain: the energy of a detected particle–the total ranges of secondary charged particles–the charge at the photomultiplier output.

The choice of a material for a radiator in a Cherenkov counter is determined by the requirements of a particular experiment. Total absorption spectrometers should not only be transparent within the Cherenkov radiation spectrum but also provide the total absorption of the energy of detected particles. In addition, in experiments on high-power accelerators, the radiator material should have high radiation resistance. In the mid-twentieth century, domestic TF-1 lead glasses containing $\sim 50\%$ of lead oxide were commercially produced, which had good transparency in the spectral range of the maximum sensitivity of photomultipliers. The radiative length X_0 in such glasses was ~ 2.5 cm, and their refractive index was $n = 1.65$. Cherenkov spectrometers of various designs with radiators made of TF-1 lead glass and heavy crystals developed at the LPI are described in preprint [4].

3. Applications of Cherenkov spectrometers in accelerator experiments

In the early 1970s, researchers at the Serpukhov accelerator began investigations with the aim of producing a 45-GeV electron beam for studying the physics of electromagnetic interactions. The necessary requirement was measurements of the electron energy (the maximum energy of particles in the experiment increased several times compared to energies in accelerator investigations performed up to that time) with a high accuracy and the maximum possible suppression of the hadron background. In this situation, the total absorption spectrometry proved to be very efficient for detecting GeV electrons and photons. The high-accuracy energy measurements were enabled by a very important parameter of the detector: its amplitude resolution $R = \Delta E/E$.

The main control element of the setup for electron beam ejection is a composite Cherenkov spectrometer consisting of two spectrometers: one with a 260-mm thick TF-1 glass radiator 300 mm in diameter, and the other with a 110-mm thick KRS-6 crystal radiator 150 mm in diameter mounted in front of the former. The material of a KRS-6 single crystal representing the solid solution of TlCl (80%) and TlBr (20%) has unique physical characteristics: the crystal density $\rho = 7.0$ g cm^{-3}, radiative length $X_0 = 0.94$, and refractive index $n = 2.2$, along with high transparency, making it quite attractive for applications as a radiator in Cherenkov counters. Such a disposition of the counters provided the total absorption of the energy of detected particles in a broad energy range (up to 45 GeV) with an energy resolution at the level of a few percent [5].

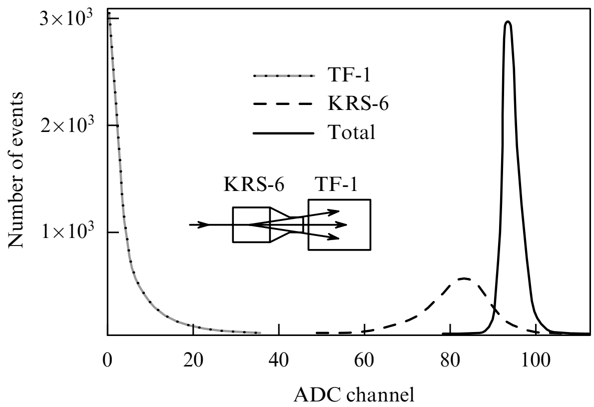

Figure 1. Energy spectra obtained by elements of a composite Cherenkov spectrometer on a 31-GeV electron beam at the U-70 accelerator at the IHEP. ADC: analog-to-digital converter.

Figure 1 depicts the energy spectra obtained with individual elements and the total spectrum obtained with the composite spectrometer for a 31-GeV electron beam with the energy resolution $\sigma \approx 2\%$. At the same time, the energy resolution of the spectrometer with a TF-1 glass radiator sufficient for absorbing showers with energies of ~ 40 GeV (300×520 mm^2) was worse, because Cherenkov photons were absorbed in the radiator.

The authors of Ref. [6] measured the total cross section for hadron absorption of photons by protons and neutrons in the electron beam produced and studied the photoproduction of ρ^0 mesons using a system for photon labeling in which photons were labelled by energy with the help of a system of CTASs with radiators made of highly transparent lead glass [7]. These detectors suppressed the intense muon background preventing measurements and ensured the production of a high-intensity beam of labelled photons.

The application field of Cherenkov spectrometers with lead glass radiators developed at FIAN was extended by using them in a universal filmless wide-aperture BIS-2 spectrometer intended for operation in a neutral channel at the Serpukhov accelerator.[1] These studies were performed within the framework of international scientific cooperation among the Joint Institute for Nuclear Research (JINR), the Central Institute of Physical Research (Hungary), the Physical Institute of Czechoslovakian Academy of Sciences, the Institute of Nuclear Research and Nuclear Energetics of Bulgarian Academy of Sciences, Tbilisi State University, and the LPI. The goal of these investigations was the search for new particles with the nonzero charm quantum number.

The electromagnetic detector of the BIS-2 setup for measuring the electron energy and the angle of electron escape from a target was a 140-channel hodoscope consisting of moduli of Cherenkov spectrometers with $100 \times 100 \times 350$ mm^3 lead glass radiators whose parameters are presented in preprint [8]. The main parameters of the hodoscope are described in detail in preprint [9]. While the energy resolution of the spectrometer demonstrated the characteristic dependence for similar detectors, $\sigma = 10/\sqrt{E}$,

[1] BIS: Filmless Spark Spectrometer (FSS).

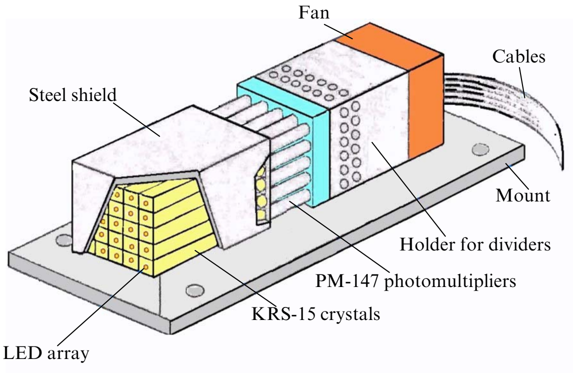

Figure 2. Schematic of a hodoscope of Cherenkov total absorption moduli used for measuring the luminosity of the H1 setup at the HERA collider.

the spatial resolution was affected by the large size of the entrance face of the module, resulting in a strong dependence of the resolution on the distance between the incidence point and the center of the corresponding module:

$\sigma \approx 9$ mm in the 20×20 mm central region of the module,
$\sigma \approx 5$ mm on the rest of the entrance face.

In 1992, investigations were started at the HERA accelerator–collider (DESY) allowing collisions of 820-GeV proton beams with 27-GeV electron beams. Researchers at the LPI participating in this work proposed a method for measuring the accelerator luminosity based on the detection of bremsstrahlung radiation produced in ep collisions. Bremsstrahlung photons and scattered electrons were detected with two hodoscopes of Cherenkov total absorption counters [10]. The construction of one of the hodoscopes (photonic, 5×5 moduli with $20 \times 20 \times 220$ mm^3 radiators) is presented in Fig. 2.

The electron spectrometer consisted of 49 moduli with $22 \times 22 \times 220$ mm^3 radiators in counters made of KRS-15 single crystals with high radiative resistance, which were earlier well studied at the LPI. The characteristics of individual moduli and their 4×4 and 9×9 assemblies were investigated in 400–650-MeV electron beams in the C-25P synchrotron, at DESY (1.5–6 GeV), and in the 29-GeV electron beam at the U-70 proton synchrotron (IHEP, Protvino). Figure 3 plots the dependence of the energy resolution of the CTAS on the energy of detected particles. The results of calculations and the accuracy of measuring the coordinates of the point of incidence of 28-GeV electrons on the entrance face of the counter presented in Fig. 4 show that the spatial resolution of the Cherenkov hodoscope can reach a level of about 0.5–0.7 mm.

By the time HERA was started up, a research team from the LPI had assembled and adjusted a suite of equipment for the luminosity monitor of the H1 detector, shown schematically in Fig. 5. The ET33 counter for detecting electrons comprised the assembly of 40 Cherenkov moduli, while the photon detector (PD) consisted of 25 moduli, and a system for suppressing the synchrotron radiation background was mounted in front of them.

These spectrometers were developed paying special attention not only to standard parameters such as the energy and spatial resolutions and fast operation but also to the radiative resistance of Cherenkov radiators and materials and components (at the level of 10^6 Gy) used in the spectrometers

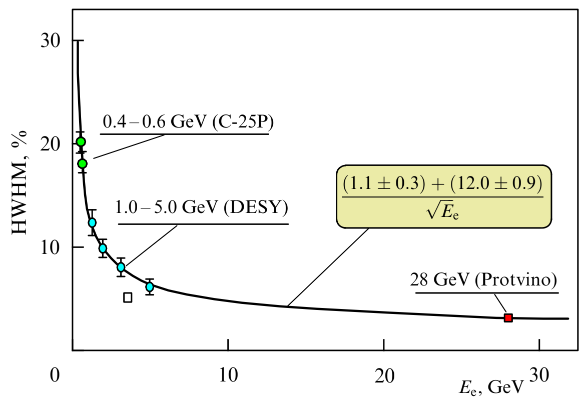

Figure 3. Dependence of the energy resolution of the module of a Cherenkov total absorption spectrometer in the H1Lumi luminosity monitor on the energy of detected electrons in the range from 0.5 to 28 GeV. (HWHM: Half-width at half maximum.)

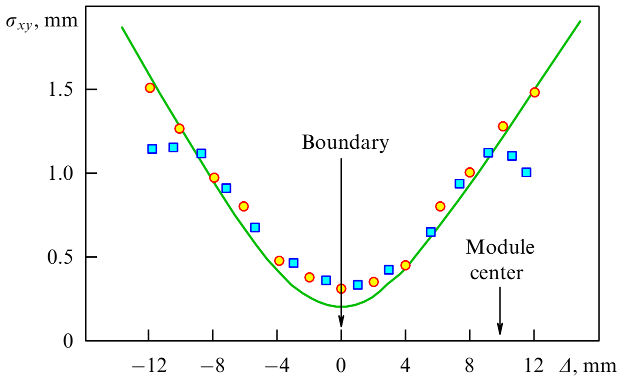

Figure 4. Spatial resolution of a Cherenkov hodoscope consisting of KRS-15 moduli obtained in measurements with 28-GeV electron beams. The curve shows the simulation of the spatial resolution by an installation of two KRS-15 moduli $22 \times 22 \times 200$ mm^3 in size. The circles and squares are experimental data for installations of two and nine moduli, respectively. Δ is the distance from the shower axis to the boundary between moduli.

[11, 12]. The operation of the luminosity monitor of the H1 detector at HERA is described in detail in paper [13]. The characteristics of detectors provided luminosity measurements with an accuracy of 1.5% during monitoring, and 1.2% after the introduction of corrections to the offline processing. From 1993 to 2007, researchers published 140 papers in this field performed at HERA with the participation of the LPI research team.

4. Conclusions

Researchers at the Department of High-Energy Physics at the LPI (earlier, the Laboratory of Photomesonic Processes) headed by P A Cherenkov performed in the second half of the 20th century a series of unique studies on the application of Cherenkov radiation for detecting relativistic particles. These studies contained the fresh ideas for the development of new measurement methods in high-energy physics, which led to creating various types of Cherenkov total absorption counters and their applications in accelerator experiments in Russia and abroad. In a number of cases, the record energy

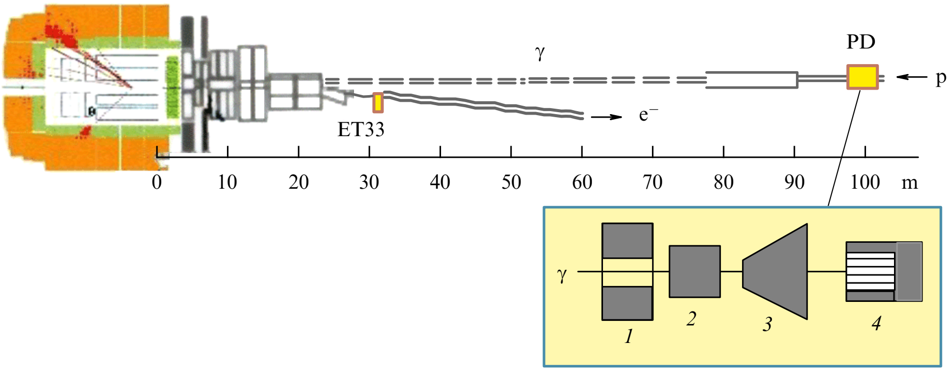

Figure 5. Schematic of the arrangement of detectors of the H1Lumi luminosity monitor in the H1 setup at HERA. ET33 is the Cherenkov hodoscope for detecting scattered electrons, PD is the hodoscope for detecting photons together with the radiative shield ($3X_0$ in total thickness) consisting of collimator *1*, absorbing filter *2*, and anticoincidence Cherenkov water counter *3*.

and spatial resolutions of the detectors were achieved, and their use in experiments proved to be decisive for obtaining positive scientific results.

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