Hermann Kolanoski

The Eye of an Experimental Particle Physicist

Elementary particles are small, so small that for the »most elementary« of them, like the electrons or the quarks, it was up to now not possible to determine any extension. To have no extension, means to be point-like in a mathematical sense. How then, you might ask, can a physicist see such particles and even determine their identities and kinematical variables? That is what I want to explain in this article: how the particles interact with the matter they are passing through, how these interactions are exploited to detect particles and how this is done in practice by a – sometimes quite huge – particle detector (see Fig. 1 in the article by zur Nedden in this Humboldt-Spektrum [1]). I will show with a selected example how physicists from the Humboldt-Universität have contributed to the development of state-of-the-art detectors.

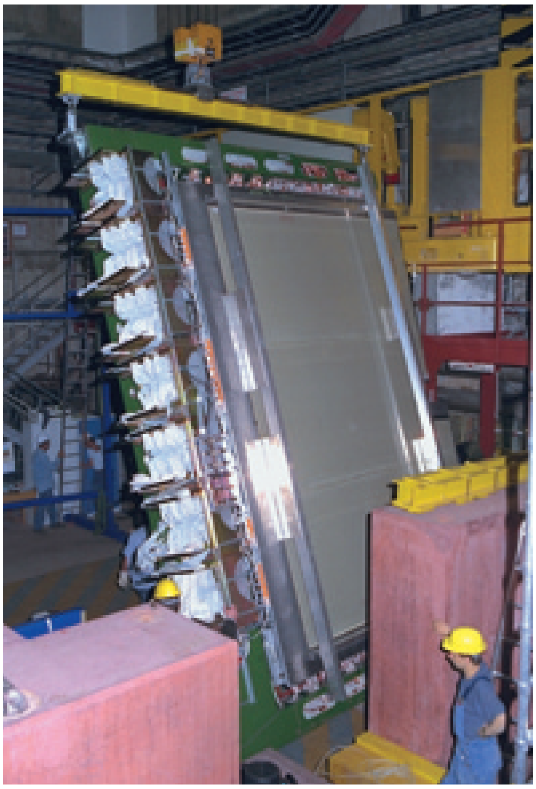


Fig. 1

Installation of a superlayer half of the Outer Tracker in the HERA-B hall at DESY. (Source: DESY/HERA-B)

Interactions of particles with matter

Think about what it means to »see an object«: light is reflected on the surface of the object, the light passes through the eye and hits the retina, the retina transforms the light quanta into electrical pulses which are carried by nerves to the brain, the brain finally puts the image together and recognizes patterns. Particle detection proceeds quite analogously.

Particles become only visible when they interact with a medium. For the detection of particles the most important interaction is the ionisation of the medium. If a charged particle passes through a medium its electrical field strips off electrons from the shell of the surrounding atoms generating electrical charges in the neighbourhood of the particle trajectory. These charges can now be used in various ways to make the particle trajectories visible. Fig. 2 shows particle tracks in an emulsion. The principle is here the same as if you expose the emulsion to light in which case the medium is ionised via the photo effect. Another classical method to make ionisation visible is the cloud chamber where the ionised atoms work as condensation nuclei and little droplets show where the particle passed (Fig. 3). In a similar way works the bubble chamber, just with the opposite transition from the liquid (usually liquid hydrogen) to the gaseous phase, the bubble. The bubble chamber was over a long time the best way to detect all details even of quite complicated particle reactions (Fig. 4).

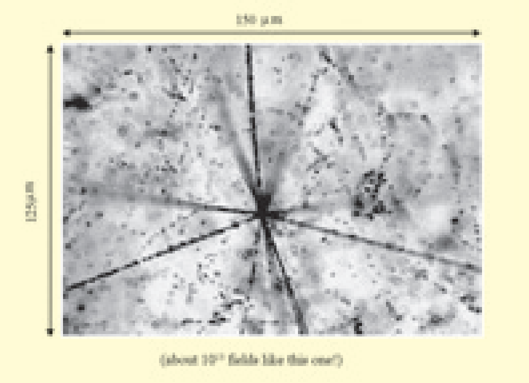


Fig. 2

Picture of a particle reaction in a photo emulsion. (Source: CERN/CHORUS)

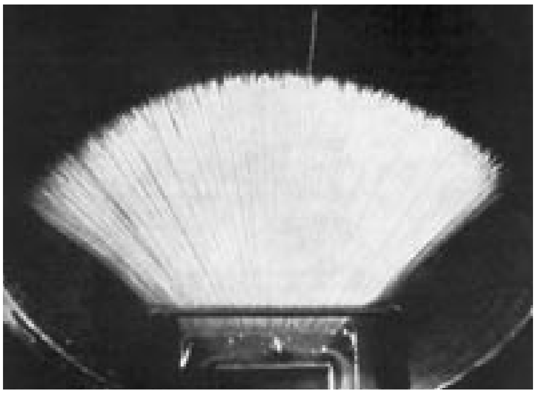


Fig. 3

Radiation of α particles from a radioactive source as seen in a cloud chamber. The range of the particles is directly related to their energy. In this picture one sees that the majority of all particles have the same energy, only one has a higher energy (corresponding to an excited nuclear state). (Source: W. Finkelnburg: Einführung in die Atomphysik, Berlin: Springer-Verlag, 1967. By courtesy of Springer-Verlag)

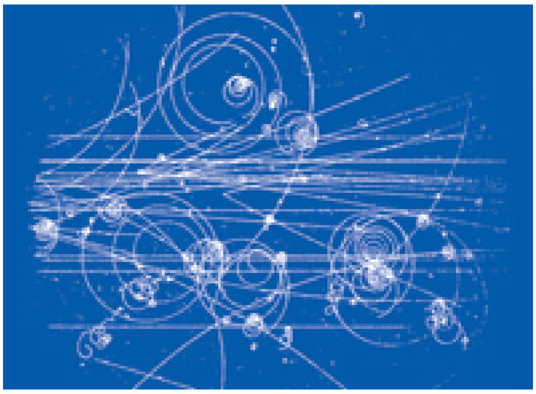


Fig. 4

Photograph of ionising particles in a hydrogen bubble chamber. The tracks have curvatures because they are bend by a magnetic field perpendicular to the picture plane. The radius of the curvature is directly proportional to the momentum of the particle. (Source: CERN)

The main drawback of these detectors is the fact that they cannot be directly read out electronically. The classical way to record the information of a bubble chamber is to take photographs in a more or less random way. In some sense you have to be lucky to find in millions of photographs the reaction you are interested in. In modern detectors the ionisation signals are converted into electronic pulses. This is much more convenient for automated data processing. Electronic signals can also be exploited to decide »online«, by fast »trigger« electronics, if a taken »picture« of an event is worth to be recorded or not.

Gaseous detectors with electronic readout

The first detector in which the ionisation was converted into an electronic signal was the well-known Geiger-Müller counter (Fig. 5), invented in 1908 and finally developed in the 1920ties at the University of Kiel. Since the charge of a single ionisation is with approximately 10^{-19} Coulomb much too small to be measurable, even using today's electronics, the charge needs to be amplified by the detector: The counter is essentially a cylinder filled with an appropriate gas (usually a mixture based on argon) with a very thin wire strung along its axis. Between the cylinder walls (cathode) and the wire (anode) a voltage is applied. After ionisation occurred in the gas volume the electrons drift towards the anode wire and are accelerated in the strong field near the wire. Very close to the wire they reach energies that allow them to ionise themselves creating eventually an avalanche of electrons (Fig. 6). With such a »gas amplification« the charge of the primary ionisation becomes measurable.

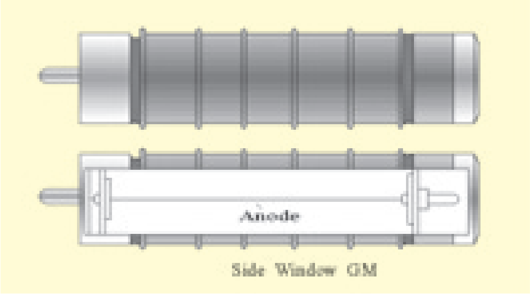


Fig. 5
Geiger-Müller Counter (Source: ORAU – Oak Ridge Associated Universities)

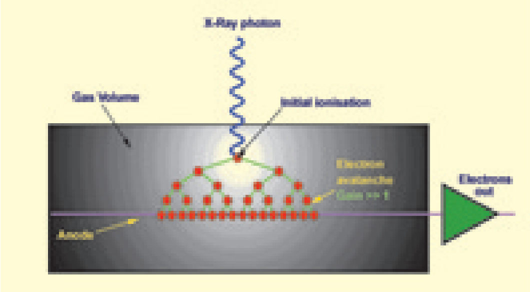


Fig. 6
Development of an electron avalanche in the strong field near the anode.
(Source: http://detserv1.dl.ac.uk/Herald/detectors_gas_detectors.htm)

Starting from this idea George Charpak has invented in 1968 at CERN the multi-wire proportional chamber, where many wires are strung in a plane with few millimetres distance. This »anode plane« is then sandwiched from both sides by two »cathode planes« (Fig. 7). The electronic signals of each single wire are read out leading to a position measurement of a particle passing through the wire plane. This delivers one coordinate in the plane; one way to get a full three-dimensional picture is to use additional planes with wires at different angles (»stereo layers«). In the 1960ties this invention, certainly not accidentally, coincided with the booming developments in electronics that allowed equipping many channels each with their own signal amplifiers.

A refinement of this detector type is the so-called drift chamber: here the time an electron needs to drift from the ionisation point to the anode is measured in additi-

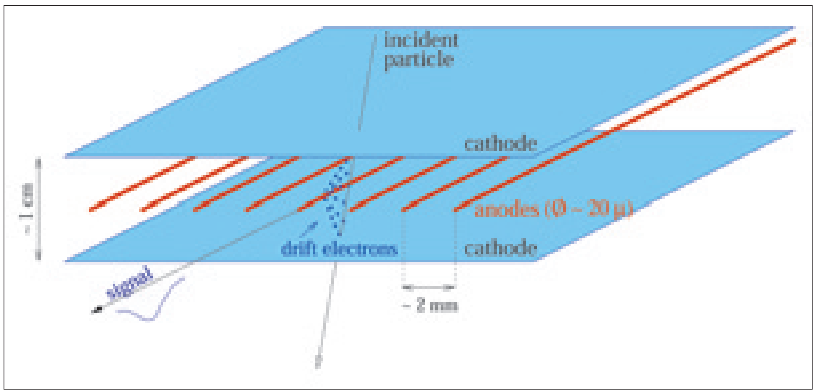


Fig. 7
Principle of a multi-wire proportional chamber.

Das »Auge« eines Elementarteilchenphysikers

Elementarteilchen sind klein, so klein, dass es für die »elementarsten« unter ihnen, wie die Elektronen oder die Quarks, bisher nicht möglich war, eine Ausdehnung zu bestimmen. Keine Ausdehnung zu haben, bedeutet im mathematischen Sinne punktförmig zu sein. Wie dann, könnte man fragen, kann ein Physiker solche Teilchen sehen und sogar ihre Identität und ihre kinematischen Variablen bestimmen? Das möchte ich in diesem Artikel erklären: wie die Teilchen mit der Materie, die sie durchlaufen, wechselwirken, wie diese Wechselwirkungen dann genutzt werden, um Teilchen nachzuweisen, und wie das dann in der Praxis mit – teilweise riesigen – Teilchendetektoren gemacht wird (s. *zur Nedden*, Abb. 1 in [1]). An einem ausgewählten Beispiel werde ich zeigen, wie Physiker von der Humboldt-Universität zu der Entwicklung von »state-of-the-art« Detektoren beigetragen haben.

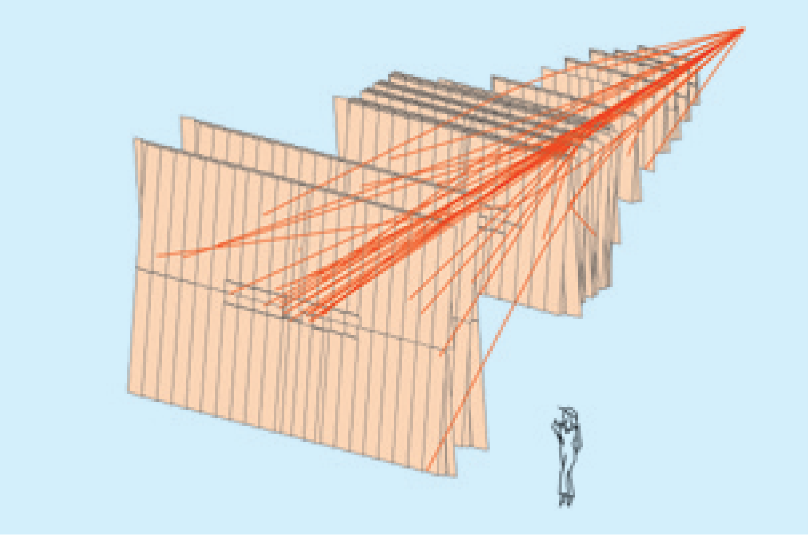


Fig. 8
The 13 superlayers of the HERA-B Outer Tracker. The red lines correspond to charged particle tracks. At the common origin of the tracks a proton has interacted with a nucleus (carbon or tungsten) of the target wire.

on and exploited for a precise determination of the position where the ionisation has occurred. The position resolution of such chambers is typically 100 to 200 µm, making them the preferred detector type for the measurement of charged particle tracks over large volumes – often many cubicmeters – in high-energy experiments.

George Charpak obtained in 1992 the Nobel Prize for his contributions to the development of particle detectors. Already in 1927 C.T.R. Wilson was awarded the prize »for his method of making the paths of electrically charged particles visible by condensation of vapour« and the 1960 prize received Donald A. Glaser for his invention of the bubble chamber. The Nobel Committee thus recognized the fact that the achievements in the understanding of the basic building blocks of matter would not have been possible without these ingenious apparatuses.

The HERA-B Drift Tubes

Groups from the Humboldt-Universität (H. Kolanoski, T. Lohse), in close collaboration with DESY Zeuthen, have participated in the development of a tracking detector employing the drift chamber principle for the experiment HERA-B. HERA-B is an experiment to study proton-nucleus interactions using the proton beam of the accelerator HERA at DESY (Hamburg) [1]. The drift chamber detector of HERA-B, called the Outer Tracker (Fig. 8), is the largest such system ever built.

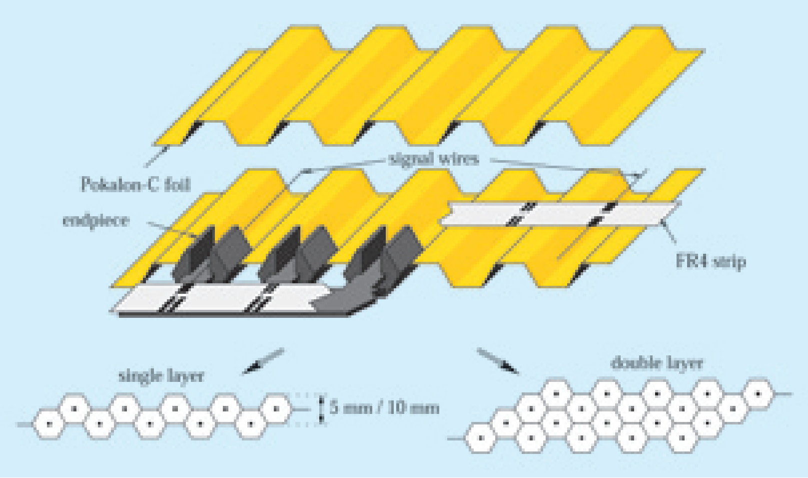


Fig. 9
Building drifttube layers from folded polycarbonat foil (yellow indicates that the foil, originally black, had to be gold-coated)

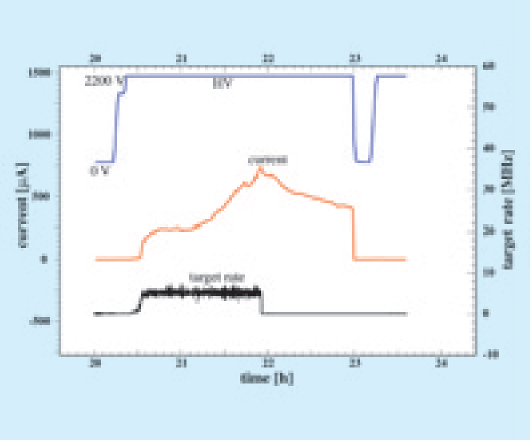
Characteristic numbers are: about 120,000 readout channels, 350 km of strung wires, 3000 m^2 of foil area, 17 m^3 of sensitive detector volume.

Besides its shear size, the detector is in many other respects a challenge: the chambers have to stand particle fluxes of up to 200,000 ionising particles per cm^2 and second. This requires a high granularity of the detector cells, fast and sensitive electronics which can handle such rates, and the detector has to be sufficiently »radiation hard« to survive in such an environment. Similar requirements are only found for the experiments at the »Large Hadron Collider« at CERN which, however, will only start in 2007. HERA-B, after its approval in 1995 by the DESY director, had to pass many obstacles which all were finally overcome by pioneering developments setting standards for coming experiments. Amongst the hardest problems to be solved was insufficient radiation hardness of detector components, a problem that endangered the whole project at several instances.

The detector consists of 13 so-called superlayers, each of them with several »stereo layers« to get three-dimensional track measurements. The largest of these superlayers cover a sensitive area of 4.5 x 6.5 m^2 (Fig. 1). The large number of layers is required to get a complete, redundant picture of an event like in a bubble chamber (Fig. 8). On the other hand a tracking detector should disturb the particle tracks as little as possible and should therefore have as little material as possible. How can one build a low mass structure that is rigid enough to allow over the large areas wire positioning with a precision of about 50 µm? We finally decided to fold hexagonal structures from a 70 µm thick polycarbonate foil to form drift tubes of 5 and 10 mm inner diameter as shown in Fig. 9. The developed lightweight multi-layer hexagonal structures are self-supporting. Since in this way the foil serves as cathode, the specifically chosen foil was soot loaded to make it conductive. It was developed by the company Bayer for various applications against electrostatic charging and was sufficiently cheap for use in mass production. Various tests showed that the foil had in many respects ideal properties: low mass density, good surface conductivity (about 120 Ω per square), mechanical stability, chemical and radiation resistance.

Aging of Detectors

The radiation hardness of the materials and of the drift tubes was tested in X-ray beams mainly by our Berlin-Zeuthen groups. When we started our development of the drift tubes the common knowledge was that the amount of charge collected per length of anode wire is



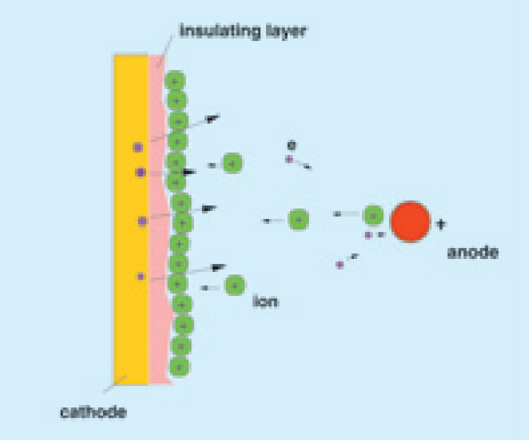


Fig. 10 (left)
»Malter currents« in the HERA-B drifttubes: With the onset of the radiation (bottom curve) starts a current (middle curve) which increases with time and does not disappear when the radiation is switched off, but only when the high voltage (HV, top curve)) on the tube is also switched off.

Fig. 11 (right)
Explanation of the Malter effect (see text).

the relevant number to determine radiation hardness of a drift chamber. Painfully, we had to learn that there are also other relevant parameters, such as the type of radiation. In our X-ray tests we collected in test chambers up to 10 Coulomb/cm, a number that is 10 to 20 times the charge per year we had anticipated for running in HERA. So we were happy with this result and after about two years of development work we were ready to put the first prototype chambers into the continuously growing HERA-B detector. What a surprise and disappointment: under the radiation generated by the proton beam the chambers started very soon to draw excessive currents that persisted even when all radiation was switched off (Fig. 10). We had to stop the mass production of the chambers which had been started in five laboratories all over the world – in Amsterdam, Beijing, Dubna, Hamburg and Zeuthen.

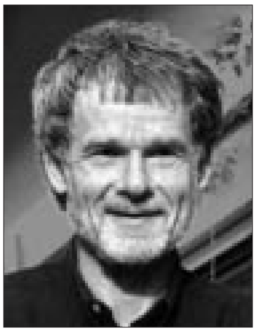
The collaborating institutes organized hastily a research and development program to find the reason for the excessive currents and to find solutions to cure this problem. Since HERA was approaching a longer shutdown, which excluded to continue the tests in the HERA beam, we began searching for a beam with which we could reproduce the effect. It turned out not to be so easy, quite similar as in the initial X-ray tests a low energy electron beam in the Hahn-Meitner Institute or low energy proton and α-particle beams in Rossendorf could not or not reproducibly ignite the currents. However we could see the effect clearly in a particular proton/pion beam in the Paul-Scherrer Institute in Schwitzerland and in a 100 MeV α-beam in Karlsruhe. We started a lengthy test beam program for nearly a year in Karlsruhe. Parallel to the test beam measurements we investigated the structure of the surfaces of the affected electrodes and the chemical composition of the deposits using different techniques, such as: optical and electron microscopy (SEM) (in cooperation with Fachhochschule Wildau) and electron spectroscopy for chemical analysis (ESCA) (Bundesanstalt für Materialforschung, BAM in Berlin).

To make a long story short: the reason for the excessive, persistent currents was an insulating layer generated by the ionising radiation in a plasma polymerisation process on the cathode foil. We had rediscovered the ›Malter Effect‹ (Fig. 11): the ions arriving at an insulating layer cannot neutralize at the cathode and a surface charge builds up. Between the cathode and this charge layer a strong electric field develops and causes eventually field emission of electrons. These electrons drift to the anode where they are amplified creating positive ions which travel back to the cathode and thus are sustaining a current which persists also after switching off the initiating radiation. The reason for the Malter currents to occur, and in particular why we did not observe it under X-ray irradiation could be clarified to a large extent. We were able to develop a model which allowed us to cure the problem: mainly with the BAM investigations we found that the soot grains in the polycarbonate foil do not reach the surface. There seems to be a thin insulating layer (of about 60 nm) which may delay the neutralization of positive ions sufficiently that in an environment of a particularly high ionisation density plasma polymerisation starts at the cathode. This leads to an additional insulation of the surface and sequentially to the ›Malter Effect‹. Even if we cannot claim to have the effect completely understood it became clear to us that we had to improve the surface conductivity of the foil. Since we had already purchased and folded the foil and since this foil had all the other tested favourable properties we investigated the possibility to improve the surface conductivity by a metallic coating. After many different trials we found a company which coated the foils with 40 nm gold on a 50 nm carrier layer of copper using a plasma technology.

This foil coating together with the proper choice of the drift gas, which is finally an Ar CF_4 CO_2 mixture, cured the Malter currents completely. Other effects of »radiation aging« then showed up (Fig. 12), but all problems could be solved by systematic development work [3]. So, after a delay of about two years the mass production of the chambers could be restarted in all laboratories (Fig. 13). In January 2000 the detector was completed and after a commissioning phase we took first data in August 2000. Results are described in [1].

Outlook

In this article I have selected an example out of the various contributions Experimental Particle Physics groups at the Humboldt-Universität have made to the development of detectors. In the HERA-B collaboration the Berlin-Zeuthen group has also contributed to the development of electronics, the data acquisition system and reconstruction software, leading to a variety of doctoral and diploma theses.



Prof. Dr. Hermann Kolanoski
Born 1945. Physics studies in Tübingen and Bonn. 1977 Dr.rer.nat. (Bonn). 1977–79 Research Fellow at Stanford University. 1983 Habilitation (Bonn). 1985 Associate Professor in Bonn, 1986 Professor in Dortmund, 1995 Professor at the Humboldt-Universität zu Berlin and Leading Scientist at DESY in Zeuthen. Research in experimental Particle Physics at the Bonn Synchrotron, the Stanford Linear Collider Center, at the storage rings PETRA, DORIS and HERA at DESY Hamburg. Research on instrumentation in Medical Physics in cooperation with the University Hospital in Essen.

Contact
Humboldt-Universität
zu Berlin
Faculty of Mathematics
and Natural Sciences I
Department of Physics
Newtonstr. 15
D–12489 Berlin-Adlershof
Phone: +49-30-2093–7604
Fax: +49-30-2093–7642
E-Mail: kolanosk@ifh.de
www-zeuthen.desy.de/
~kolanosk/

Now we are turning to new endeavours and challenges: In the HERA-B experiment we are currently busy with the analysis of the accumulated data [1]; another group is working on the analysis of data from the ZEUS Experiment running in the colliding electron-proton beams of HERA [2]. The future will see us busy looking into the sky for either high-energy photons [4] or high-energy neutrinos [5]. In both cases the Cherenkov light emission generated by secondary interactions of these particles, either in the atmosphere (photons) or in the compact Antarctic ice (neutrinos), is detected. The explanation of this detection technique deserves another article.

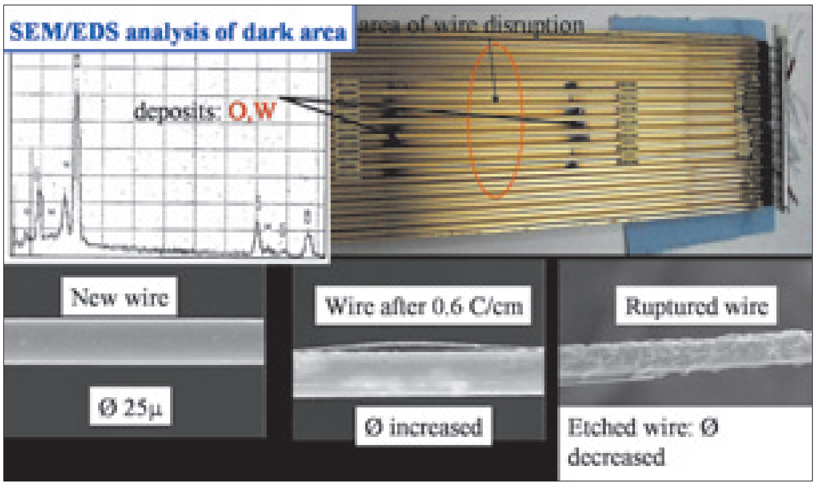


Fig. 12
Radiation aging in drifttubes. Upper right: optical inspection of an opened test module; upper left: chemical composition of deposites on the cathode; bottom: increasing destruction of an anode wire by radiation. (Source: DESY/HERA-B (Diss. A. Schreiner, Humboldt-Universität zu Berlin, 2001)).

The particle physics community has, in a remarkable international consensus, decided that the next step to the investigation of the fundamental structure of the micro- and macro-cosmos is a Linear Collider in which electrons are collided with positrons, their anti-particles. Questions as for the nature and origin of the »dark matter« in the universe and the dimensionality of our world should be tackled with such a machine. With the recent recommendation of an international panel to use the superconducting accelerator technology developed at DESY within the TESLA project [6], Germany is extraordinarily honoured and, at the same time, has also been given special responsibility. The Humboldt-Universität groups have been engaged since some time in development work for both the machine and detectors at this machine. An example is the development of a polarized positron source for the injection into a Linear Collider (participating Humboldt-Universität groups of T. Lohse, N. Pavel and myself). This work is done in a test beam at the Stanford Linear Accelerator Center (SLAC) in an international effort. The problems to be solved there are new for us and not less challenging than the previously managed tasks. As in all our work we have to face the possibility to fail, but without that the life of a scientist would be much less thrilling.

References

[1] *zur Nedden, Martin et al.:* Probing the Formation Process of Matter with Charm and Beauty Quarks; in this Humboldt-Spektrum.
[2] *Pavel, Nikolaj:* Deeply Probing Quarks and Gluons; in this Humboldt-Spektrum.
[3] *Albrecht, H. et al. (HERA-B Outer Tracker Group):* Aging Studies for the Large Honeycomb Drift Tube System Of the Outer Tracker Of HERA-B, Nucl. Instrum.Meth.A515:155–165,2003.
[4] *Lohse, Thomas/Pavel, Nikolaj:* Astroparticle Physics with Very-High-Energy Photons; in this Humboldt-Spektrum.
[5] AMANDA/IceCube Experiment: http://www-zeuthen. desy.de/nuastro/
[6] TESLA Technical Design Report: http://tesla.desy.de/new_pages/TDR_CD/start.html. See also: http://www.interactions.org/linearcollider/

Fig. 13
Production of drifttube modules. The folded foil layers are fixed in templates, the wires are soldered into the profiles and then covered by the next foil layer and so on. (Source: DESY/HERA-B)