Observations on cathode aging (Malter effect) in honeycomb drift chambers under high irradiation load

K. Berkhan[a], G. Bohm[a], H. Kolanoski[b], A. Schreiner[a], U. Schwanke[a], V. Souvorov[a], C. Stegmann[a], U. Uwer[b], M.Walter[a]

[a]DESY-Zeuthen, Platanenallee 6, D-15735 Zeuthen, Germany

[b]Institut für Physik, Humboldt-Universität zu Berlin, Germany

Presented by G. Bohm

The Outer Tracking (OTR) system for the HERA-B detector at DESY [1,2] consists of honeycomb drift tubes with cathodes folded from Pokalon-C foil, a soot-containing polycarbonate, operating with CF_4-containing drift gas. The first prototypes, exposed to radiation in HERA-B, suffered radiation damage ascribed to the Malter effect (ignition of self-sustaining discharges). We present the results of investigations of cathode surface properties and include a semiquantitative discussion of the ion-layer formation process. The achieved understanding was important for the development of a radiation-hard detector.

1. Introduction

A mechanism to create and sustain corona discharges, commonly denoted as Malter-effect [3], is quite frequently observed in gaseous detectors with high gas amplification. Its main characteristics is the build-up of a positively charged ion layer on the cathode surface. This is possible if the neutralisation of ions is sufficiently delayed by a layer of high resistance covering the cathode. "Malter" electrons can then be liberated at the cathode, are amplified at the anode and thus feed a self-sustaining, local discharge. The corresponding observations are increasing chamber currents, which do not disappear after stopping the irradiation, but are sustained at a comparable level, generally until the HV is switched off.

After the first observation of this effect in prototype tests of the OTR chambers at the HERA-B experiment, an intense R&D program was launched with the aim to find workable solutions for this important detector part as early as possible. The complete history of these investigations is found in [4,5], where also further details of chamber construction, running and beam conditions, and the observed effects are given. Here we restrict ourselves to discussing the results of an analysis of the cathode surface properties (section 2) and a semiquantitative description of the ignition mechanism, in order to better understand the observed strong dependence on the nature of irradiation (section 3).

For easy reference, some important chamber parameters are given below:

- cell size: 5 mm, 10 mm (inner diameter of hexagonal cell shape)
- anode wire: gold-plated tungsten, diameter 25 μm.

The cathode material was 75 μm thick foil of untreated Pokalon-C, a polycarbonate based on Bisphenol-A with a soot content of 6%, yielding a surface resistivity of about 100 Ω (producer Lonza). The gluing of the cells was done by epoxy (Araldite AW106, hardener HV953U, Ciba-Geigy) and in addition by small amounts of conductive glue to provide electrical contacts between chamber layers (E-solder 3025, IMI). If required, it was cleaned with isopropanol.

In the following, we compare non-irradiated (unused) with "irradiated" cathode foil samples. The irradiation conditions we are referring to here are those for the first observation of the Malter effect in prototype chambers tested in the HERA-B detector[1]:

- HV: 2250 V, gas gain: $\sim 2.5 \cdot 10^4$
- field strength: 340 kV/cm (anode), 1.7 kV/cm (cathode)(for 5 mm cells)
- gas: CF_4/CH_4 80%/20%, typical gas flow 1 Vol/h
- type of irradiation: secondaries from 920 GeV/c p-N interactions
- accumulated charge (for first observation): ~ 3 mC/cm
- mean irradiation current density: up to $0.05\,\mu$A/cm

2. Surface properties of Pokalon-C

In order to substantiate the principal assumption that the ignition of a Malter discharge requires the existence of an insulating layer on the cathode surface, we studied the surface properties of irradiated and non-irradiated foils of Pokalon-C with three different methods:

1) direct measurement of the resistance between thin (diameters ~ 1 mm) contact tips on opposite sides of the foil,
2) chemical analysis using electron spectroscopy (ESCA) of the surface, performed by the Bundesanstalt für Materialprüfung, Berlin, and
3) scanning secondary electron microscopy (SEM) of the surface, performed at the Technische Fachhochschule Wildau.

It was not possible to detect any irregularities of surface conductivity with the first method; its strong dependence on the pressure applied to the contact tips prevented any clear conclusions.

[1]Gas mixture and operation point were changed for the final detector [4]

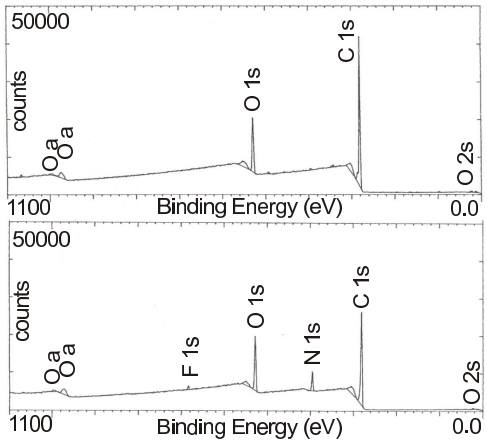

Figure 1. ESCA spectra from non-irradiated (top) and irradiated (bottom) cathode foil surfaces.

Using the ESCA method [6], photoelectrons from a surface layer $3-10$ nm deep are analysed, with sensitivity to the chemical binding of various atoms. For the investigated samples of both irradiated and non-irradiated foils, general observations were the absence of signals from soot at the investigated spots and, consequently, charging-up of the samples.

Comparing the spectra (see fig. 1), in the irradiated case additional signals of fluorine and nitrogen (in organic bounds) are found, besides the expected C, O groups from Bisphenol A. The former, F and N, were suspected to originate from the dissociation products of CF_4 and outgassing from the glue as the hardener HV953U is based on a modified polyaminoamid. The comparison of the 1s peaks of carbon (fig. 2) shows a broadening in the irradiated case, a characteristic of plasma polymers.

The foil surface can also be investigated with a SEM, applying the third method, when it is conductively fixed to the sample holder. The SEM pictures, displaying the surface-dependent fluctuations in secondary electron yield, were found to lose contrast suddenly, when the primary electron energy was lowered below a certain threshold (0.9

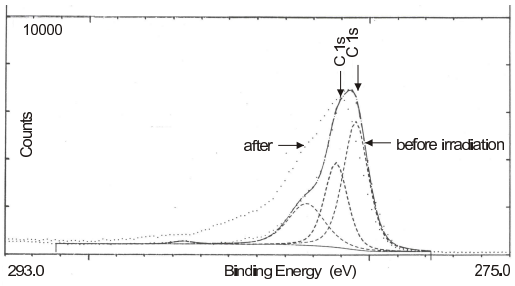

Figure 2. High resolution ESCA spectra of the C(1s) peaks from fig. 1 before and after irradiation.

keV). This behaviour could be restricted by various surface treatments: plasma etching, mechanical scraping, erosive treatment by the electron beam of the SEM itself, or conductive coating (graphite or metallic), and it was characteristic for Pokalon-C foil of thickness 75 μm. It was neither found for thinner (15 μm) Pokalon-C foil, nor for the carbon-loaded polyimid surface of the cathods used in ATLAS-type straw detectors. [2]

The only explanation found was that the surface of untreated Pokalon-C has, due to lack of soot, much less than bulk conductivity within a depth of less than 100 nm from the surface, and therefore can be charged up if the range of the scanning electron beam becomes shorter, thereby destroying the imaging conditions of the secondary electron optics.

3. Dynamics of Ion Layers (Influence of Test Beam)

A very important result of our aging studies concerning the Malter effect is a strong dependence on the irradiation conditions, preventing a description by only one parameter, like the accumulated charge per cell length. In small (15 cm length) chambers under 35 keV X-ray irradiation, no Malter effect was seen up to 4.5 C/cm, while in hadronic beams of sufficiently high energy (350 MeV/c π/p, 100 MeV α, and at HERA-B itself) self-sustaining currents were excited within hours [4,7]. In chambers with 10 mm cells, the effect was observed with considerable delay compared to 5 mm cells; no quantitative study of the influence of cell size was performed, however.

In addition, a specific memory effect was found: chambers which had shown the Malter-effect in a first irradiation, developed the effect in a subsequent irradiation faster than new chambers. It was even possible to reexcite the Malter effect with radiation from a ^{55}Fe source or an X-ray beam.

Below, we give a rough description of the physical processes, which may account for these observations. At a given place on the cathode, the surface density of ions, $n(t)$, obeys an equation of the form

$$\frac{dn}{dt} = j_+ - j_- \ ,$$

where j_+ is the number of ions per area and time, reaching the cathode, j_- the number of neutralisation processes per area and time. If there exists an insulating layer of resistivity ρ and permittivity $\varepsilon = \varepsilon_r \varepsilon_0$, the current density across this layer will be given by $n/(\varepsilon\rho)$ if the electric field strength in the insulating layer is dominated by the deposited charge. If a surface ion density $n(t)$ is created, it will decay exponentially with a time constant

$$\tau = \varepsilon\rho = 2 \cdot 10^{-13}\mathrm{s} - 3 \cdot 10^{3}\mathrm{s} \ (\varepsilon_r = 3) \ ,$$

where the limiting values are given for Pokalon-C (bulk resistivity $\rho = 7.5 \cdot 10^{-3}\Omega$m) and pure polycarbonate without soot ($\rho \approx 10^{14}\Omega$m), respectively. Consequently, an ion layer cannot be accumulated in the first case, while in the second case it could grow until the insulating layer breaks through, depending of course on $j_+(t)$ as will be discussed below. It should be emphasised, that the thickness of the insulating layer does not enter here directly, as long as a bulk resistivity can be meaningfully assigned. A very thin layer, with a resistivity that is hard to measure, can be sufficient for the first ignition of a stationary

[2] No Malter effect was observed for the TRD detector of HERA-B [1], based on the ATLAS straw technology and being irradiated simultaneously with our chambers in some of the irradiation tests.

discharge. This layer can then grow by plasma polymerisation if the gas has the required properties. This would lead to the memory effect mentioned above, which was typically found for gases containing CH_4 [4]. (The gas finally chosen was $Ar/CF_4/CO_2$ 65:30:5; while the effect was not completely inhibited by this gas, in some cases annealing was observed).

For a given charge Q, produced at the anode by a track crossing the cell perpendicular to the wire, the current density at the cathode (at radius $r_2 = 5$ mm) is given by

$$j_+ = \frac{Q}{\Delta t \cdot \Delta z \cdot 2\pi r_2} \ ,$$

where $\Delta z \approx 30\mu$m is the axial extension of the ion cloud, and $\Delta t \approx 1\mu$s is its time spread, when arriving at the cathode (the numerical values are estimated from drift and diffusion parameters of ions and electrons from [8]). For minimum ionising particles (MIP) in 5 mm cells, $Q \approx 10^6 e$, but this value may be multiplied by a factor 100 (or more) in case of heavily ionising particles (HIPs).

If $\Delta t << \tau$, a charge layer of density

$$n = j_+ \Delta t \approx 3 \cdot 10^{-7}\mathrm{C/m^2} \ (3 \cdot 10^{-5}\mathrm{C/m^2})$$

per MIP (HIP) would be created, producing a field strength (in the case of HIPs) of the order of 10 kV/cm, much larger than the normal field strength of 1.7 kV/cm at the conductive cathode surface. With the working hypothesis that such a field is sufficiently effective in liberating electrons, then, presumably, a Malter discharge can be ignited by a single HIP.

For 10 mm cells, one finds by scaling Q , Δt , Δz , r_2 by the appropriate factors 2, 4, 2, 2 respectively, that $j_+(10\,\mathrm{mm}) = j_+(5\,\mathrm{mm})/8$, while $j_+\Delta t$ is still reduced by a factor 2 (in case of HIPs with a range less than r_2 the scaling of Q by a factor 2 does not apply and the reduction factor of $j_+\Delta t$ becomes 4). Of course, also the radiation doses were generally lower and the bigger gap may lead to less stable conditions for self-sustaining discharges.

A possible reason for the failure to excite Malter discharges with X-ray irradiation (using a 35 kV X-ray tube with Mo-cathode[7]) may be the more diffuse electron cloud produced in the interaction of X-ray quanta with the gas or wall atoms: While Q is not much larger than the value for MIPs (the energy loss of a MIP in 0.5 cm of chamber gas is 17 keV, the mean energy of X-ray quanta about 20 keV), Δz is at least one order of magnitude larger (the range of 10 keV electrons is ~ 0.5 mm). As this makes single-photon ignition improbable, a charge layer may only be accumulated for sufficiently large τ: In the stationary case, a mean value of n is found from

$$\langle n \rangle = \tau \langle j_+ \rangle = \rho\varepsilon\langle I \rangle / (2\pi r_2) \ ,$$

where $\langle I \rangle$ is the linear current density, which is usually chosen not to be larger than about 0.5 μA/cm to limit space charge effects. To produce a field strength of the order of 10 kV/cm as above would require $\rho = 3 \cdot 10^8\,\Omega$m. If this value is reached for a plasma polymer produced in a previous Malter discharge, re-ignition with X-rays will be expected.

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