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# Micro-channel plates and vacuum detectors

T. Gys *

*CERN, PH Department, CH-1211 Geneva 23, Switzerland*

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ABSTRACT

A micro-channel plate is an array of miniature electron multipliers that are each acting as a continuous dynode chain. The compact channel structure results in high spatial and time resolutions and robustness to magnetic fields. Micro-channel plates have been originally developed for night vision applications and integrated as an amplification element in image intensifiers. These devices show single-photon sensitivity with very low noise and have been used as such for scintillating fiber tracker readout in high-energy physics experiments. Given their very short transit time spread, micro-channel plate photomultiplier tubes are also being used in time-of-flight and particle identification detectors. The present paper will cover the history of the micro-channel plate development, basic features, and some of their applications. Emphasis will be put on various new manufacturing processes that have been developed over the last few years, and that result in a significant improvement in terms of efficiency, noise, and lifetime performance.



## 1. Introduction

The development of conventional photomultiplier tubes (PMTs) was started in the 1930s. In these vacuum devices, single photons are converted in photoelectrons by a photocathode. This charge is amplified by a chain of discrete dynodes to a level matching the sensitivity of standard electronics. Dynodes are basically structures emitting secondary electrons when hit by primary charged particles, low-energy electrons in the present case. In PMTs, the dynodes are each operated at increasing bias voltage and through repeated secondary electron emission processes, charge signal amplification occurs. Various dynode configurations exist: linear, cage, venetian blind, box-and-grid, fine mesh, etc. The complexity of their mechanics and biasing circuitry makes them difficult to fabricate; it does not allow for compact structures that would be more robust in e.g. magnetic field environments. In the late 1990s, the metal channel dynode technology allowed for the fabrication of more compact PMTs. These devices essentially maintain the performance of conventional tubes, in particular their single photon sensitivity. They can be segmented in arrays of typically $8 \times 8$ or $16 \times 16$ mm-size elementary cells. They are however not suited for applications where very high spatial ($\leq 50$ μm) and/or timing ($\leq 50$ ps) resolutions are required. In this case, alternative technologies for photon detection and amplification based on micro-channel plates (MCPs) may be exploited.

The present paper will cover the history of the MCP development, some of the MCP basic features, and applications in high-energy physics. Emphasis will be put on various new MCP manufacturing processes that have been developed over the last few years and that result in a significant improvement in terms of efficiency, noise, and lifetime performance.

## 2. History

### 2.1. The channel electron multiplier

The concept of a continuous dynode for the multiplication of electrons was proposed for the first time by Farnsworth [1]. His apparatus essentially consisted of two devices encapsulated in an evacuated glass envelope (Fig. 1). The first device was generating a modulated electron stream that was subsequently collimated and directed towards a second device acting as an amplification stage. The key elements of that stage were a hollow resistor and a filamentary electrode coated with a secondary emitter material (Th or Ba) and extending axially of the resistor. By a potential applied across the resistor, a graduated longitudinal electrostatic field is produced. Prior to active operation, the filament is heated up to incandescence; the secondary emitter material is vaporized from the filament surface and deposited onto the inner surface of the resistor. During active operation, as the primary electron stream is striking the resistor inner surface, secondary electrons are created. They are accelerated longitudinally by the graduated electrostatic field but also transversally by the filament supplied with an appropriate bias voltage. These electrons

* Corresponding author. Tel.: +41 22 767 8307; fax: +41 22 766 8640.
*E-mail address:* Thierry.Gys@cern.ch

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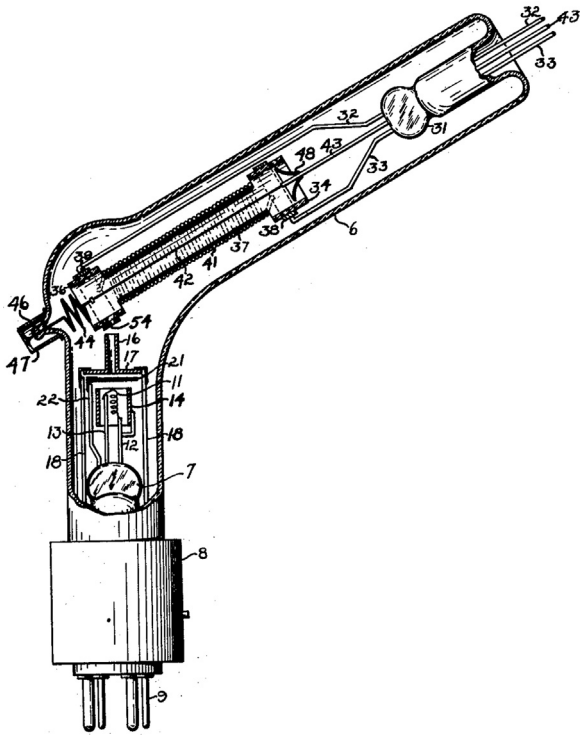


**Fig. 1.** The first channel electron multiplier developed by Farnsworth [1].

hit the opposite resistor surface, causing again a release of additional secondary electrons. This effect is repeated and contributes to the overall electron amplification process. This first electron multiplier proved to be linear up to the point where space charge effects started to dominate.

Further implementations of electron multipliers were delayed until the early 1960s, when much experience on secondary electron emission had been acquired [2] essentially through the development of PMTs. At the same period more suitable materials became available. More particularly, earlier work by Green and Blodgett [3,4] showed that after appropriate hydrogen treatment at high temperature, lead silicate glass exhibits the properties of electrical conductivity and secondary emission.

The original concept of Farnsworth was improved by Oshchekpov et al. [5]. These authors described the operation of a simpler electron multiplier based on the same principle of continuous secondary electron amplification, but without central focussing electrode. For the inner channel coating, a mixture of $TiO_2$ and MgO was found to satisfy the conductivity, secondary emission yield and stability requirements. The complete fabrication process including the preparation of a ceramic tube was detailed. Systematic studies of the secondary emission coefficient, multiplier gain and output current in function of the applied voltage were carried out. Finally, these authors introduced the parameter $\alpha$ as the ratio between channel length and diameter. It turns out that most of the electrical performance of electron multipliers depends on $\alpha$. As will be seen below, this characteristic opened the way to any dimensional reduction of the electron multiplier as soon as the technology would permit.

Heroux and Hinteregger [6] developed a windowless resistance strip magnetic electron multiplier for the detection of extreme ultraviolet radiation. Based on a planar geometry, the device consisted of dynode and field strips made of glass and internally coated with high-resistance tin oxide and antimony. Appropriate external voltages establish an electric field between the strips and voltage gradients along both strips. A magnetic field is applied perpendicular to the electric field and parallel to the strip surfaces. These crossed magnetic and electric fields result in secondary electrons refocussing on the dynode strip and producing secondary electrons. Through the repetition of this process, current amplification is achieved. With this magnetic electron multiplier, DC gains up to $10^8$ have been measured.

A similar magnetic electron multiplier development was carried out by Goodrich and Wiley [7]. Their device structure subsequently evolved towards very small, tubular continuous dynode channels [8]. At their metallized ends was applied a potential of 1 to 2 kV and no magnetic field was required. By grouping these channels in parallel arrays, current density distributions could be determined. This paved the way towards potential applications that include image intensification. It was also confirmed experimentally that for a constant parameter $\alpha$ and channel diameters ranging from 0.04 to 0.004 in, the same high gains were achieved.

The principle and basic characteristics of channel electron multipliers (CEMs) have been thoroughly described in the literature [9–11]. They will not be discussed in detail in the present paper. One important and detrimental effect to be mentioned however is ion feed-back that may become important at high gains ( $\geq 10^5$). The charge pulse at the channel output may create residual gas ions. These are accelerated back toward the channel input where they may produce further secondary electrons that are in turn multiplied. The consequences of ion feed-back are multiple: the primary output charge pulse is followed by smaller ones, the channel capacity is decreased and the device lifetime is directly affected. One way to mitigate these ion feed-back effects is to curve the channel. With this geometry, an ion will strike the channel wall at lower energies and the probability to generate secondary electrons is decreased. Curved channels are however difficult to assemble in arrays. The ultimate gain limit with curved channels is driven by space-charge effects near the output [12–14].

Single CEMs are robust and efficient detectors of positive and negative ions as well as electrons and photons. Various CEM models suited for specific applications e.g. in space and mass spectrometry are available on the market. An early example of application is the work of Johnson [15]. The performance of a curved CEM was assessed in the vacuum ultraviolet range (300–1700 Å) where the CEM detection efficiency was seen to be similar to that of tungsten. Green et al. [16] exploited the fast-timing characteristics of some CEMs by measuring half-lives of nuclear levels in $^{59}$Co and $^{170}$Yb with a precision of 20 ps.

### 2.2. The micro-channel plate

As mentioned in the previous section, the fundamental electrical characteristics of a CEM basically depend on the length-to-diameter ratio $\alpha$. Consequently, the channel size can be reduced to a limit set by the technology, and a number of these channels can be bonded together to form an array with imaging capability. The very first MCPs were assembled with many single small-diameter CEMs bonded together [11]. This rather rudimentary process was superseded by fiber drawing techniques. These originally made use of hollow channels that have subsequently been replaced with “billets” having etchable glass core and non-etchable glass cladding. The manufacturing steps are as follows [10,11]. The billets are heated and drawn down to typically 0.8 mm diameter fibers. Thousands of such fibers are bundled together to form a hexagonal rod. The rod is drawn again and several such rods are fused together to form a MCP “boule”. The boule is sliced in MCP wafers that are further polished and chemically etched (Fig. 2). Individual MCPs are heated under reducing hydrogen atmosphere to provide electrical conductivity and secondary emission. Typical surface resistivity values for such treated glass reach $10^7$ to $10^{13}$ Ω/□; the latter figure corresponds to a typical MCP resistance of $10^9$ Ω. Electrodes generally made of NiCr are deposited on the MCP input and output faces. The MCPs finally undergo pre-conditioning through electron scrubbing in order to stabilize their operation.