Simulation of a Vacuum Phototriode with SIMION 3D

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Abstract

An electron-optic model of a 26 mm diameter vacuum phototriode (VPT) photodetector was developed using SIMION 3D software extended by additional code to simulate secondary emission at the dynode. The predictions of the variation of gain with magnetic field for mesh anodes with 100, 40 and 7 lines per mm and fields from 0 and 4T are presented. The predicted time development of the signal at 0T is presented and compared with experimental data obtained by illuminating a production VPT for the electromagnetic endcap calorimeter of CMS with 60ps laser pulses at a wavelength of 435 nm.

Introduction

The vacuum phototriode (VPT) is a single gain stage photomultiplier which is very insensitive to high magnetic fields compared to a multi-stage device. It has been chosen as the photodetector for the homogeneous lead tungstate endcap electromagnetic calorimeter of the Compact Muon Solenoid (CMS) experiment [1] which is currently under construction at CERN, Geneva, Switzerland. In the endcap region the VPT is located in the full 4T magnetic field of the CMS solenoid. Other VPT have been used in a previous generation of particle detectors, for example the endcap calorimeter of OPAL [2] and the STIC of DELPHI [3]. A VPT for CMS is shown schematically in Figure 1.

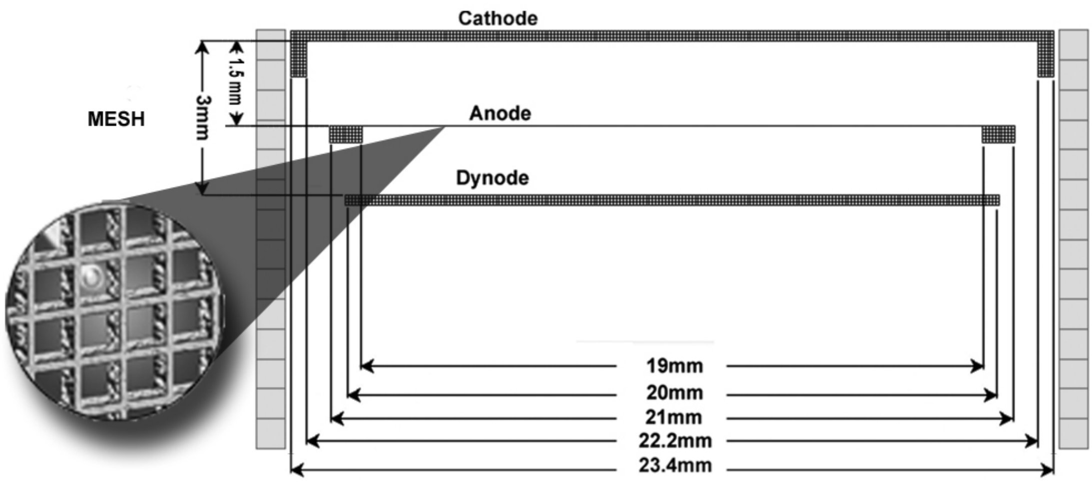

Figure 1 Schematic of a CMS production VPT. The outside diameter of the tube is 26 mm. Only the parts modelled in the SIMION 3D simulation are illustrated. The

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anode is made up of a metal ring supporting a thin mesh with a transparency of approximately 50% over a diameter of 19 mm.

Photoelectrons from the cathode are accelerated towards the anode by the high electric field. The anode is a partially transmitting metal mesh and the primary electrons that are not directly captured are slightly decelerated before hitting a solid dynode with a high secondary emission coefficient. The secondary electrons produced at the dynode are accelerated back towards the anode where a fraction are collected; these produce the bulk of the signal flowing in the external circuit. Those transmitted are decelerated in the anode-cathode gap, return to the anode, where a further fraction are collected, and then back to the dynode where a further generation of secondary electrons can occur.

The simple planar geometry, coupled with small inter-electrode gaps, suggests that such a VPT structure should be fast and have good timing resolution. In this preliminary study we discuss a simulation of a model of a CMS production VPT [4] using an extended version of the SIMION 3D electron optic simulation software and present our predictions for gain at fields from 0 to 4T. We have also made an initial measurement of the relative time delay as a function of operating potential of a VPT illuminated by 60 ps laser pulses at a wavelength of 435 nm.

Simulation

To simulate the VPT we used version 7.0 of the commercial ion/electron optic simulation program SIMION 3D™ [5]. This enables the tracking of electrons or ions through static electric and magnetic fields defined by a three-dimensional geometric electrode model. SIMION tracks the path and calculates the time-of-flight of each particle, but once a particle hits an electrode the data relating to the particle is stored and the particle is lost. In order to simulate the secondary emission from a VPT dynode we have integrated SIMION with our own code which uses the hit position of the primary electrons on the dynode as the source of secondary electrons whose time origin is now equal to the flight time of the primary. This process is repeated until the incident energy of an electron hitting the dynode has fallen below a user-defined threshold.

The detailed simulation of the mesh anode is a critical element in our studies. SIMION allows for an “ideal mesh” which is fully transparent and exists just to define a surface at a constant potential through which ions or electrons can pass unhindered. In our VPT we have two different length scales at which we must simulate a potential array and track electrons. The basic size of the VPT, and its inter-electrode gaps, is on the scale of millimetres however the anode mesh in production tubes has 100 lines per millimetre in two orthogonal directions. In order to avoid splitting the macroscopic dimensions of the VPT into millions of fundamental cubes whose side (“grid-unit” *gu*) would be of order 5 micrometres we used the concept of multiple instances. The large scale structures are simulated at a resolution of 0.083 mm per gu with an ideal (100% transmission) anode mesh in order to generate the correct electrostatic potentials. Superposed on top of the ideal mesh is a very thin cylindrical volume in which a real (i.e. capable of absorbing particles) mesh is simulated at a spatial resolution appropriate to the mesh being modelled. We simulated three different meshes each with 50% optical transmission. One mesh had 7 lines per millimetre (0.032 mm per gu), one had 40 per millimetre (0.006 mm per gu) and a third with 100 lines per millimetre (0.005 mm per gu). The 100 lines per millimetre mesh simulates the anode mesh fitted to production VPT.

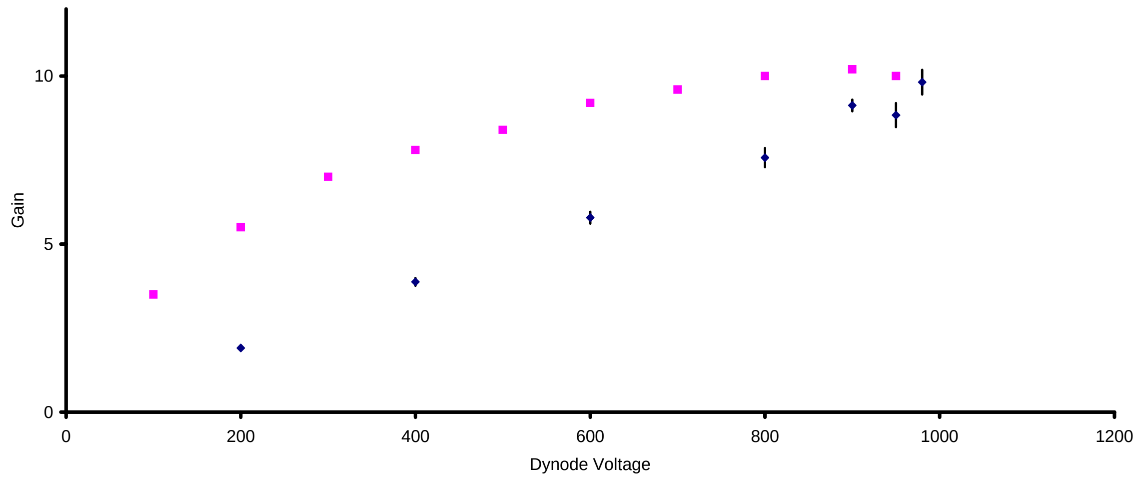
The modelling of the dynode secondary emission is currently very simple. This is deliberate as we wish to understand exactly what contributes to different experimentally observed aspects of VPT performance, and with a simple model one level of complexity is removed. We used a multiplicative factor which only depends on the incident energy of the primary electron incident on the dynode. At any given energy a constant number of secondary electrons are produced, each with an initial energy of 5 eV. The emitted angle is randomly varied by up to 5 degrees from the surface normal.

Gain at 0T

The gain of the VPT depends on the secondary emission of the dynode and the transparency of the mesh. A simple model [6] predicts that a transparency of around 50% is optimum. The planar geometry with small inter-electrode gaps should also result in a very fast pulse with short transit time. Although it is already known from beam tests that the speed of response of the VPT for CMS is fast (< 10 ns) it has not yet been directly measured.
The predicted and measured gain, as a function of dynode voltage, at 0T field for a production VPT with a 100 lpm mesh are shown are shown in Figure 2. In order to obtain reasonable agreement for absolute maximum gain the secondary emission gain *G* was modelled as

$$G(V_{K-D}) = \frac{V_{K-D}}{40}$$

where V_{K-D} is the potential difference between the Cathode and the Dynode and the



units are Volts.

Figure 2 The absolute measured gain of a real VPT (upper data points) and a simulated VPT (lower data points standard error on the mean) as a function of V_{Dynode} for an anode potential of +1000V and grounded photocathode.

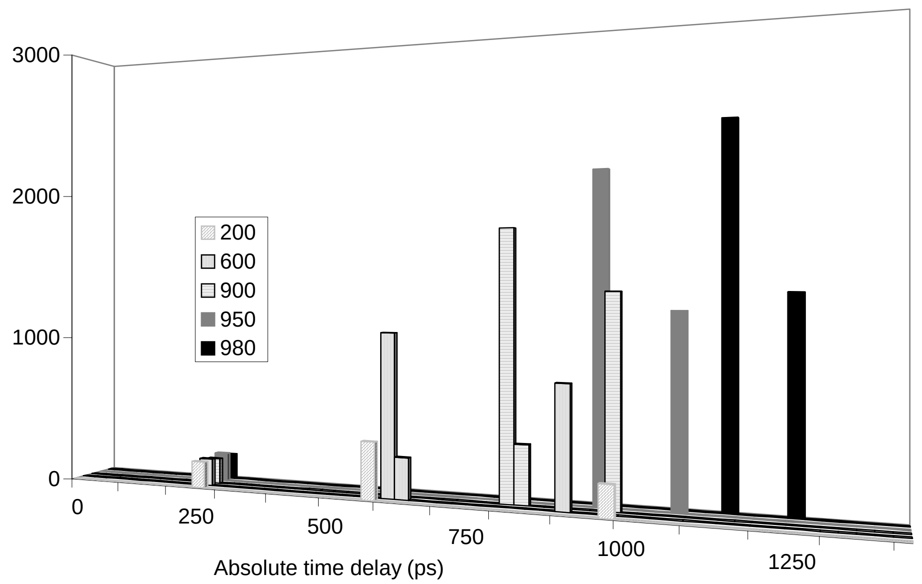


Figure 3 The simulated arrival times of electrons at the anode for different dynode voltages. The anode potential is fixed at +1000V. The small peak at 250 ps are photoelectrons directly collected by the anode. The vertical scale is proportional to the gain of the device.

The simulated arrival times of electrons on the anode is shown in Figure 3. There is an increasing transit time with increasing Dynode potential as the accelerating potential between the Anode and Dynode decreases and thus the average velocity of the secondary electrons decreases too. A preliminary measurement of relative delay has been made and is described in the next section.

Response to fast laser pulsed illumination at 0T

A preliminary experimental verification of the predicted variation of the time delay of the anode signal with dynode potential when illuminated by a fast light pulse has been made. The centre of the photocathode of a production VPT, at 0T, was illuminated by fast pulses (60 ps FWHM at 435 nm) from a PicoQuant SEPIA 808 diode laser. The cathode of the VPT was held at -1000 V, the dynode at variable negative potential, and the anode DC coupled to the 50 ohm input of a digital oscilloscope (LeCroy WavePro 950, 1GHz analogue bandwidth, 16 giga-samples per second). The rise-time of the leading edge (10% to 90%) was around 600 ps, although this was in part limited by the oscilloscope bandwidth of 1GHz.

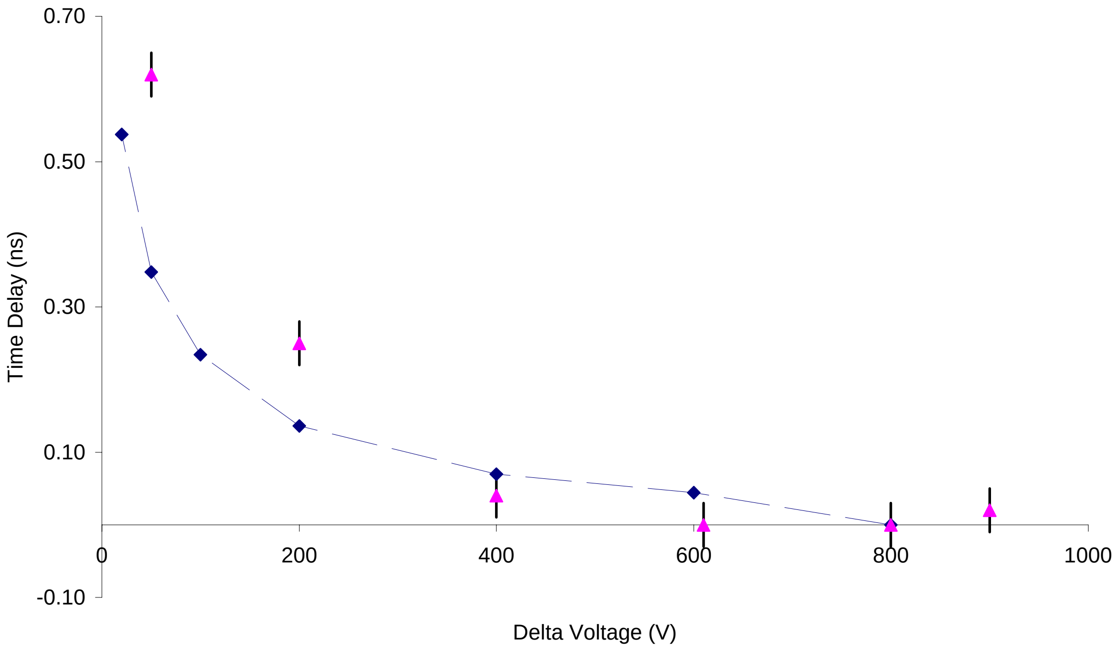


Figure 4 The delay from laser trigger to the peak of the anode signal as a function of the anode to dynode potential difference. Experimental data from a production VPT is shown as data points with estimated systematic error shown. The points with curve to guide the eye are the time delay (mean collection time) from a SIMION simulation of a VPT with 100 lpm mesh. The time difference is defined to be zero at a voltage difference of 200 V for both the experimental and simulated data.

The data shown in Figure 4 show the expected trend of decreasing delay with increasing potential. Since the potential differences are much higher than the typical initial energy of a secondary electron one would expect that the time delay should decrease as $1/\sqrt{V_{A-D}}$. Both the experimental and simulated data are well described by such a relationship (R^2 of >0.97).

Gain at fields up to 4T

The response of the VPT to magnetic fields is of paramount importance for its application in CMS. Tubes will be located in the full 4T field. The axis of rotational symmetry of the VPT will lie at angles from 8 to 26 degrees to the magnetic field dependent on their location in the endcap. Our QA procedures for the production VPT evaluate their angular response to a field of 1.8T and batch sample their relative gain at a fixed angle of 15 degrees to a 4T field. One aim of this programme of simulation is to check that nothing unusual is predicted to happen at other angles at the full field. To demonstrate the effect of the mesh pitch on the relative gain as a function of field we simulated a production VPT with three different mesh pitches. Figure 5 shows the simulated variation of gain as a function of magnetic field. In each case only the central 6 mm diameter of the photocathode is a source of photoelectrons.

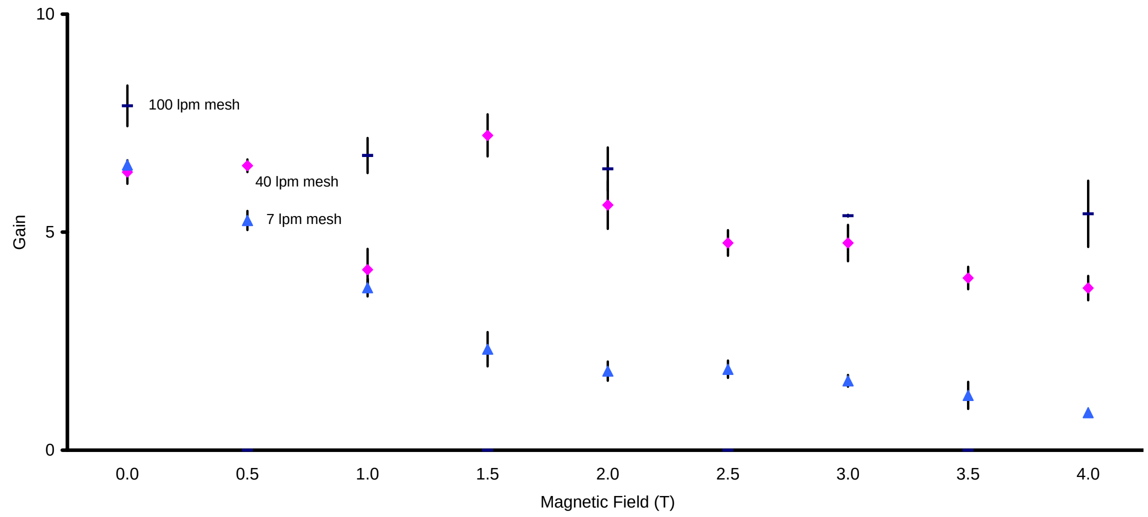


Figure 5 The simulated variation of gain with field for a VPT at an angle of 15 degrees to the field for three different mesh sizes (each with 50% transparency). The anode and dynode voltages were 1000V and 800V respectively. The standard errors on the mean are shown. The response of the100 lpm mesh is only simulated at integer values of the magnetic field.

Conclusions

We have demonstrated that a SIMION simulation of a production vacuum phototriode reproduces the major features (0T gain and relative time shift) of a real device. However the simple dynode model does not reproduce the gain saturation effect seen in real devices. The effect of changing from fine meshes to a coarse mesh (7 lpm) illustrates a dramatic fall in gain as a function of magnetic field compared to the fine mesh used in production tubes.
We plan to improve the realism of the dynode secondary emission model, to include saturation, statistical fluctuations of the gain and a more realistic model of the energy spectrum of the secondary electrons. We will also make further measurements of the time response and investigate the effect of manufacturing tolerances, such as gap variation or angular misalignment of the dynode, on the performance of the VPT in high magnetic fields.

Acknowledgement

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