Meshing Challenges in Simulating the Induced Currents in Vacuum Phototriode

S. Zahid and P. R. Hobson

Electronic and Computer Engineering, Brunel University London, Uxbridge, UB8 3PH UK

Introduction

Vacuum phototriodes (VPT), which are single gain-stage photomultipliers, have been used as photodetectors for many years in particle physics experiments. For example, they were used in the OPAL experiment at LEP [1] and are currently used in the endcap electromagnetic calorimeter of the CMS experiment [2], at CERNS's Large Hadron Collider. Existing VPTs are fast, low-gain devices that can operate in strong magnetic fields at angles up to approximately 40 degrees from the axis of cylindrical symmetry.

The VPTs contains three main electrodes with the aim to convert a light source into a signal of amplified electrons that is proportional to the light magnitude. The charged particle tracing module is used to generate the electron trajectories and enables us to determine the time-dependent currents with and without an external magnetic field applied. The secondary emission feature within COMSOL is also used to simulate the secondary emission particles created upon collision of the primary particles with the dynode. These are accelerated back towards the anode, some of which may pass through the anode and turn around to repeat their trajectory. For the final stage, probes are used within the model to analyse the findings of the simulations. A parameter of critical practical importance is the induced current on the anode. This is calculated using Ramo's theorem with an appropriate weighting potential. The current is calculated automatically at each time step.

Timing response is a property of VPTs that also needs to be considered to ensure there is no overlap occurring within its applications.

Theory of VPT

A VPT consists of three electrodes; photocathode, a fine planar anode mesh and dynode in parallel. The layout in Figure 1 illustrates schematically the layout of the RIE FEU-188 VPT which is used in CMS. The first electrode layer is the photocathode, followed by the mesh anode and then the electron multiplying dynode. The role of the photocathode is to convert light into photoelectrons. These photoelectrons are released from the photocathode when light, with a photon energy greater than the work function, illuminates the faceplate. These are then accelerated through a fine metal anode mesh (array of squares holes) to a solid dynode. The dynode generates secondary electrons which amplifies the signal.
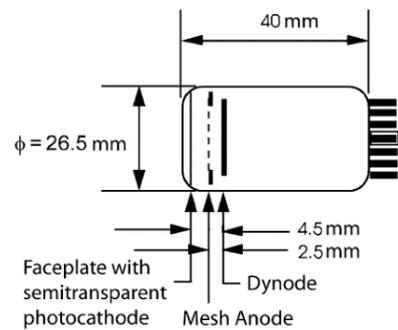
Figure 1. Outline showing the key dimensions of the RIE FEU-188 VPT used in the CMS experiment. The mesh anode has 10 µm pitch and is 50% transparent.

The secondary electrons are accelerated and a fraction collected at the anode. The induced current on the anode provides the output signal.
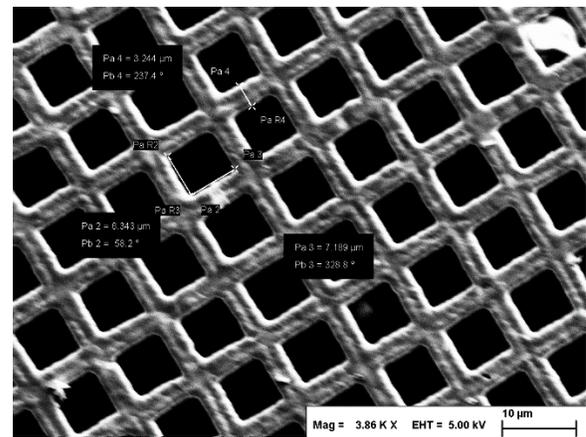
Figure 2. This shows the dimensions of the anode mesh determined using a scanning electron microscope.

A RIE VPT has been dismantled to determine the precise dimensions, particularly the thickness, of the anode mesh. Figure 2 and Figure 3 show images of the anode mesh generated using a scanning electron

microscope. Measurements taken from these images indicate a square hole of about 6×6 µm² and the thickness of the mesh to be approximately 1.5 µm.
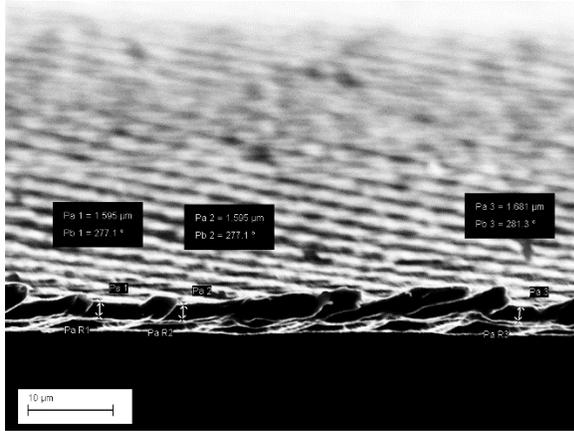
Figure 3. Image taken through a scanning electron microscope showing the thickness of the anode mesh.

Simulation Setup

We have simulated the RIE FEU-188 structure using COMSOL V5.3. The model includes a very fine, thin anode mesh with a 10 µm pitch and 50% transparency. There is a deviation of approximately ± 5.25% of the pitch when compared to the anode mesh in Figure 2. This allows 50% of the electrons travelling through the VPT to pass through the anode mesh and the other 50% will be absorbed. The electron trajectories and induced currents on the anode are modelled using the electrostatics and charged particle tracing modules within COMSOL. The electrostatics module was used to determine the electric field within the VPT with cathode, anode and dynode potentials of 0 V, +1000 V and +800 V respectively. These are the maximum operating potentials for the real VPT.

Numerous challenges were encountered, the most difficult is to apply a finite element mesh (FEM) within COMSOL of the VPT. The main issue being the many orders of magnitude difference in scale between the VPT electrode diameter of approximately 20 mm and the fine anode mesh with a thickness of 2.5 µm. Over 8.5 million domain elements are produced and each of which is typically a factor of one hundred to one thousand times smaller than the separation of the electrodes or their surface areas. This created an issue of an inverted boundary at the corners; problems with the minimum element size and issues with memory utilisation and computation time. The results presented here used a workstation with a four-core (plus hyperthreading) Intel i7 processor @3.7 GHz and 48 GB of RAM. This paper discusses the simulation challenges, the steps to

enable a realistic area of mesh to be simulated and finally we present results on the induced current as a function of time for a device operating in magnetic fields up to 4 T in strength.

The Shockeley-Ramo Theorem [3] is used to calculate the induced current within the VPT through the instantaneous changes of electrostatic flux. The induced current caused by the flow of photoelectrons within the VPT can be calculated from:

$$i = -q \cdot \vec{v} \cdot \vec{F_k} \qquad (1)$$

Where q is the charge of the photoelectron, and $\vec{v}$ is its instantaneous velocity. $\vec{F_k}$ is the weighting field (not the electric field) which is determined by setting the potential of the anode to unit potential. The remaining electrodes (cathode and dynode) are set to zero potential.

For the simulation set up, the geometry has cylindrical shape which acts as the VPT tube. The tube contains a vacuum and has external and internal dimensions matching those shown in Figure 1.

Based on the dimensions of the square holes of the real anode mesh shown in Figure 2, the COMSOL model would contain over five million equivalent square holes in the simulated geometry of the anode mesh. In practice, to run this model in COMSOL V5.3 using the workstation mentioned earlier, the mesh was simplified to a 150 x 150 grid of square holes. This was the maximum number of holes achievable at the time without getting meshing errors or running out of memory.
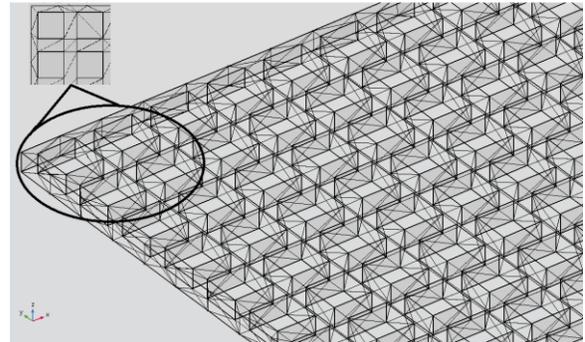
Figure 4. Screenshot of the anode mesh within COMSOL with COMSOLs FEM.

The initial stages of the model design consist of creating the geometry for the VPT as well as applying the most suitable material to the internal components. The material for the internal space is a vacuum. The dynode material is based on Aluminium Gallium Arsenide, which is an alternative to KCsSb; provided by COMSOL. This is material was chosen as an alternative is it is a commonly used material within photomultiplier tubes (PMT) and has a high secondary

emission coefficient. The anode is made up of a metal mesh, for which the material nickel is used.

For the simulation, the electrostatics module plays a central role in defining the static properties of each electrode. The electric field of the VPT is then generated based on the potential of all the components. The Charged Particle Tracing (CPT) module then defines the cathode layer as a source for primary electrons. These particles are released at right angles to the surface and then accelerated towards the anode, by the electric field. The CPT module then produces the trajectory for each primary electron. In the scenario where the particle avoids the anode mesh and hits the dynode, the dynode then releases secondary emissions based on the energy and direction of the respective primary electron. These secondary electrons are accelerated back towards the anode.
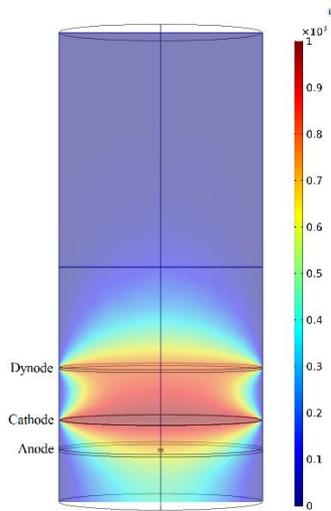
Figure 5. Screenshot showing the electric potentials within the VPT tube. Cathode is set to 0V potential. The colour bar represents the electric potential in volts.

Once the material and physics properties are defined on each component within COMSOL, a tetrahedral mesh is created on the whole VPT so that the modular physics can simulate finely detailed outcomes throughout the VPT. Two separate mesh sequences are defined within the VPT, the first is based on the internal and external geometries, and the second is focused solely on the anode mesh. They are processed separately as the dimension of each tetrahedral edge is very significantly smaller on the anode mesh than the rest of the VPT. The FEM for the whole VPT consists of 8534251 domain elements, 1485338 boundary elements, and 495636 edge elements. The computation time is approximately 14 hours and uses approximately 20 GB memory.

The studies are the final part to the simulation setup. There are two defined studies, the first focuses on the simulation of all the static properties using a stationary solver. The second study focuses on the particle trajectories and collisions based on a time dependent solver. The time taken for all the electrons to reach the end of their trajectories is on the scale of a few nanoseconds, with the simulation time ranging from 0 ns to 3 ns in steps of 0.05 ns.

Simulation Results

The aim of these simulations is to understand and visualise the activity that occurs within the VPT. The basic properties can be understood through the particle trajectories and their respective induced currents. Figure 5 shows the static electric field produced by study 1.

Figure 6 shows the particle trajectories within the VPT with a magnetic field of 0 T. Photoelectrons are released at the cathode towards the anode and dynode. They are released at varying initial energies to simulate light at various energies hitting the photocathode. Those that hit the dynode emit secondary electrons (for this simulation, only a single electron is released to observe its behaviour).
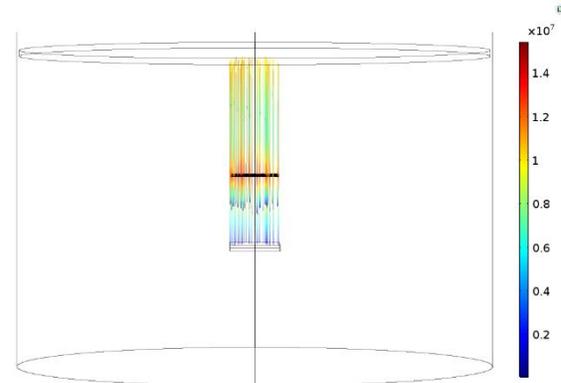
Figure 6. Particle trajectories of electrons released from the photocathode towards the dynode. The colour bar represents the particle velocity in m/s.

Figure 7 shows the induced current produced by four distinct scenarios for the photoelectrons travelling within the VPT. The first scenario is the primary photoelectron hitting the anode mesh directly (~50% chance). The second scenario is if the electron is transmitted through one of the anode mesh holes, then the primary photoelectron is likely to hit the dynode. This results in a secondary emitted electron which may go on to hit the anode. The third scenario is for the primary photoelectron to hit the dynode without producing a secondary electron. The fourth scenario is when a secondary electron is accelerated back towards the anode which it does not hit. Instead it goes past the anode and heads towards the photocathode. The kinetic energy will reduce to zero and at this point it is attracted back towards the anode, which has the

greater electric potential. In the case shown in Figure 7 and Figure 8, it goes past the anode again without hitting it and repeats the cycle back and forth around the anode until it eventually hits the anode.
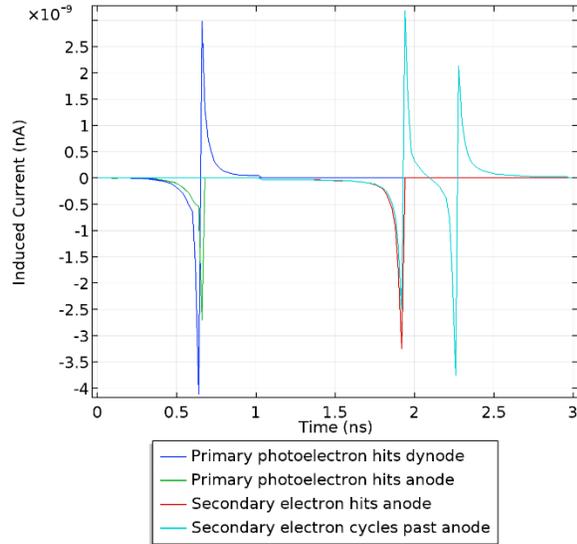
Figure 7 - A simulation of the induced currents in an RIE FEU-188 VPT due to a single electron in 4 different scenarios, with the VPT at 0 T field.

In Figure 7 and Figure 8 the dark blue curve represents the induced current on the anode for particles that have not passed through the anode. The green curve represents the induced current at the anode when the particles go through the anode mesh and collected at the dynode. The red curve represents the induced current at the anode when secondary emissions produced by the dynode are collected from the anode. And finally, the light blue curve represents when the secondary emission from the dynode goes back through the mesh and towards the dynode.
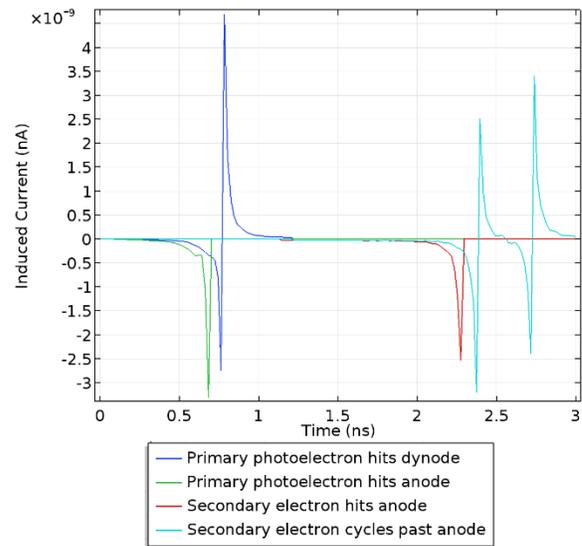
Figure 8. A simulation of the induced currents in an RIE FEU-188 VPT due to a single electron, with the VPT at 15° to an axial 4T field.

Figure 9 shows the movement relative to the VPT geometry of the same particles from Figure 8, in the Z axis. The trajectories show a clearer picture of the particle movement for each scenario.
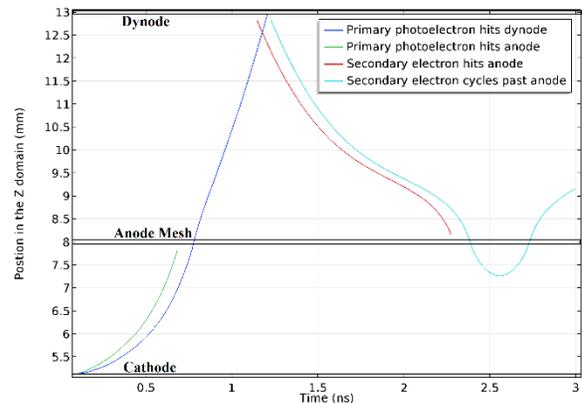
Figure 9. This shows the location in the Z domain of the selected particles in Figure 8.

Figure 10 shows the electron velocity of the z component for each particle. Figure 11 shows the electron energy in electron volts for each scenario in Figure 8.
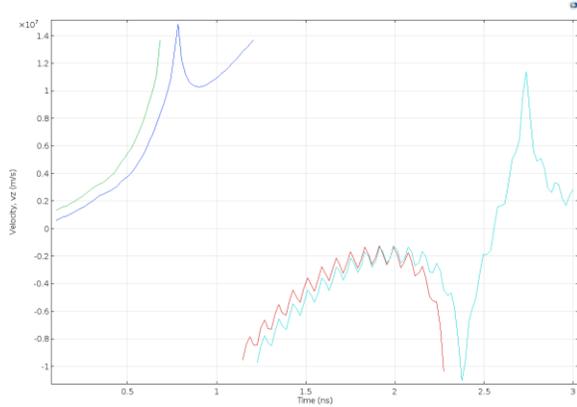
Figure 10. Component of electron velocity along the axis of cylindrical symmetry in m/s.
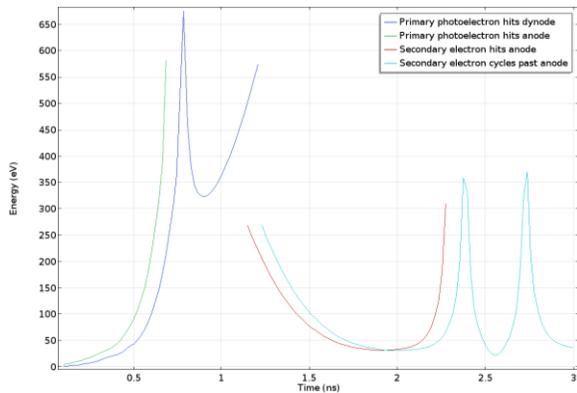
Figure 11. Electron energy in electron volts (eV).

Conclusions

We have shown the challenges in developing a COMSOL model of a vacuum phototriode where the critical dimensions of the fine anode mesh are ~ 1000 times smaller than the typical areas of the mesh and the other two electrodes. Even with a fairly powerful multi-core PC and 48 GBytes of RAM we were unable to simulate more than about 1% of the actual mesh area. We have shown that with careful attention paid to the meshing and with the improvements available in the latest version of COMSOL (V 5.3 at the time of writing) a large enough area of fine mesh can be simulated that plausibly realistic results can be obtained.

Our current work is focussed on comparing the performance of the real VPT, with its additional stray impedances with the predictions of the COMSOL model. Modelling the geometry of the connections to the electrodes and using the RF Module should enable a more realistic simulation of the signal observed in reality.

Improvements towards the simulation may be achieved by parallelising the computation across a GPU cluster.

References

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Acknowledgements