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The mesh PM for the AMS Time Of Flight, comparison between simulation and measurements

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Abstract

A simulation of fine mesh photomultipliers (PM) has been performed in order to understand their behavior in a magnetic field, in view of their use in the Time Of Flight system of the AMS-02 experiment, which is a cosmic ray spectrometer to be operated in space after 2006. The model on which the phototube simulation is based is described and a comparison with the experimental data are given. The simulation results can account for the apparent fine mesh low gain and bad single photoelectron resolution. The time response of a fine mesh in a magnetic field has been investigated with the use of the Monte Carlo, which also turned out to be a useful tool in understanding the change of PM gain as a function of the angle between the magnetic field and the PM axis. All the Monte Carlo results agree quite well with the data taken.

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1. Introduction

The Alpha Magnetic Spectrometer (AMS) will be the first large acceptance magnetic spectrometer to be installed on the International Space Station and will measure cosmic ray fluxes for at least 3 years in a low orbit (about 400 km) around the earth [1]. It will detect rigidities up to 2.5 TV, by using a superconducting magnet providing a maximum field of 0.87 T. The photo-multiplier tubes of the plastic scintillators of the Time Of Flight System of AMS-02 will operate in the strong (2–3 KG) and badly shaped fringing field of the dipole magnet [2]. This has led to the choice of the R5946 Hamamatsu "fine mesh" tubes, for their intrinsic capability of tolerating the magnetic field [3]. Since the year 2000, a special purpose Monte Carlo simulation was written in order to understand the time behavior in magnetic field of the fine mesh photomultipliers [4]. Later the Monte Carlo was developed to reproduce the gain characteristics and the single photoelectron spectra shapes obtained in the laboratory [6] Finally, the

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model–data comparison enabled us to identify those parameters which required detection with the PMs calibration. In the following, the model on which the complete simulation of the fine mesh phototubes is based, is given and some features of it are described.

2. The model of the simulation

The basic model of the fine mesh simulation starts with a single photoelectron (phe) extracted from a random point on the surface of the photocathode. Then, the phe is followed, by solving the equations of motion with the electric and magnetic fields, in the approximation of a uniform electric field, up to the first dynode. The distance between cathode and first dynode is 3.4 mm and the voltage drop is twice that for the following 16 dynodes whose spacing is 0.9 mm.[1] The phe impinging on the first dynode surface extracts secondaries, up to a maximum number, until all the available energy is used. Therefore the simulation implements multiplication on an energy basis and not by using a poissonian distribution of secondaries as in other models previously simulated (see the one described in Ref. [7]). In the actual energy computation, the phenomenological energy distribution of the secondary electrons shown in Fig. 1 is used, taking into account the energy given to the whole lattice and the minimum energy threshold for extraction (the work function of the dynode bialkali surface being about 2.1 eV). This threshold energy is chosen to be a smooth function of the angle of incidence of electrons on the mesh, θ_{inc}, which is related to the angle θ between $\vec{B}$ and the PM axis, since for high θ there are more inclined electrons. In fact, at a higher angle of incidence θ_{inc} on the dynode surface, secondary electrons are extracted more easily [8,9] (the extraction of secondary electron is a surface phenomenon, and highly inclined electrons are closer to the surface).

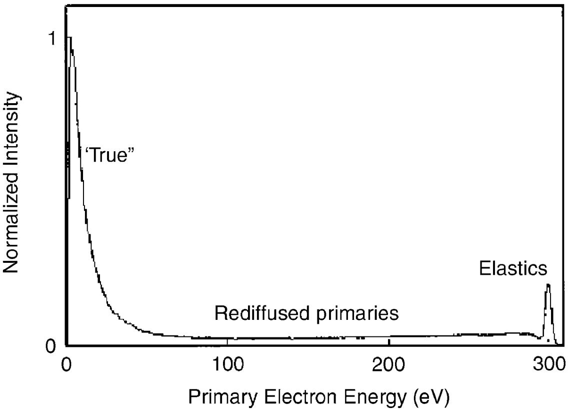

Fig. 1. Phenomenological distribution of Secondary Electrons Emitted (SEE) energy at the dynodes [7], for a primary electron of 300 V (the secondaries can be divided in "true", "rediffused" and "elastically scattered" [9]).

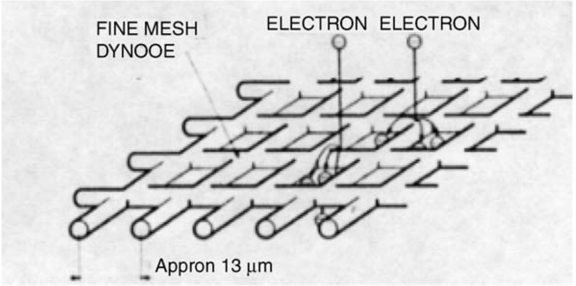

Fig. 2. Structure of a fine mesh dynode: mesh step and diameter of Hamamatsu R5946 are respectively 13 μm and 5 μm [3].

The dynodes are a planar mesh of orthogonal wires (Fig. 2 shows a mesh). The phe can thus pass through a hole of the first dynode, without extracting secondaries, and go to the next stage (the cathode also is semitransparent, and the photon can interact at the first dynode of bialkali material [10], but this is actually not implemented in the model). This kind of "loss" is valid for each dynode and is a reason that the fine mesh needs more multiplication stages than a normal venetian blind PM [11], even if the "loss" is more critical for the cathode-first dynode stage [10]. This possibility has been implemented in the model as an overall probability (namely the *transparency* T) whose value has been tuned with real data and is described in the next section.

After the first dynode, each extracted electron is followed to the second one, and so on, by solving the equations of motion; electrons outside the

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[1] The partition ratios being 2:1:1:1:1:1:1:1:1:1:1:1:1:1:1:1:1.

dynode boundaries are lost and the effect of the transparency is taken into consideration. The multiplication avalanche is followed up to the anode. A proper indexing algorithm is used in order to identity each electron in the avalanche. Thus, the kinematical information can be recorded for all the electrons at the dynodes and finally up to the anode.

Using this basic model, it was possible to simulate the various experimental conditions and obtain the different spectra to be compared with the data taken.

3. The fine mesh 'transparency'

In the literature, various simulation studies have been done in order to account for the fine mesh dynodes 'holed' structure, with the resulting probability that an electron of the phototube avalanche could 'jump' into those holes (see Refs. [7,15]). The transparency parameter T adopted by this simulation study in order to account for the 'holes' of dynodes, has been found to be very efficient in tuning the model to the experimental data.

The value of the transparency is not merely the geometrical factor holes/wires-surface ratio, because of the bending field lines that attract the electrons on the mesh grid. The effective value of T has been tuned to reproduce the gain of a typical tube working at 2000 V, and turned out to be $T \sim 20\%$. Nevertheless, the transparency is related to the High Voltage (HV) of the PM, as seen from both data and simulation: starting from simulation, at fixed HV, the relation between gain and transparency has been found; then, on looking at the data, the experimental gain at different High Voltages was fitted with a linear dependence between T and the power supply, which can be seen in Fig. 3. In fact, this may be understood since at higher HV, the electrons are directed more efficiently onto the electrode wires and the probability of missing the surface decreases.

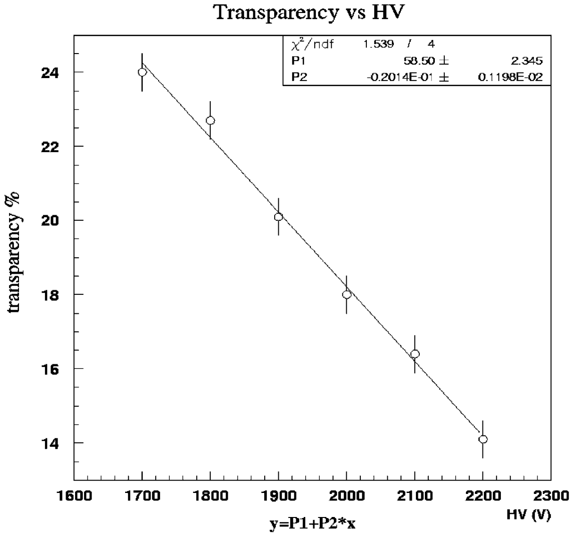

Fig. 3. Relation between T and HV as found from both simulation and experimental data.

As already mentioned, the transparency helps to explain why the fine mesh needs more stages of multiplication than normal 'venetian blind' phototubes (16 compared with nine for Hamamatsu R5946 and R5900 [3], used respectively for the TOF of AMS-02 and AMS-01). Nevertheless, the transparency T depends geometrically on the electron angle of incidence (θ_{inc}) on the planar mesh ($T \propto \cos\theta_{\mathrm{inc}}$) and decreases for highly inclined electrons. In the magnetic field, we thus have contrasting effects on the phototube: as θ increases, the magnetic field which curves the electrons onto the walls causing the primary loss, leads also to a higher average inclination of the electrons and therefore a geometrically lower T, with a consequently lower T-loss. Moreover, the higher inclination of electrons also favors the secondary electrons emission from the dynode surface. The final result is an increase in the gain of the fine mesh with the angle θ, both in the data and the simulation, up to a maximum angle, as will be shown in Section 6.

4. Single photoelectron response

Starting from the basic model, an appropriate program was written to reproduce the single photoelectron (sphe) spectrum as measured in the laboratory (the spectrum was made by collecting the PM response to several low light led pulses

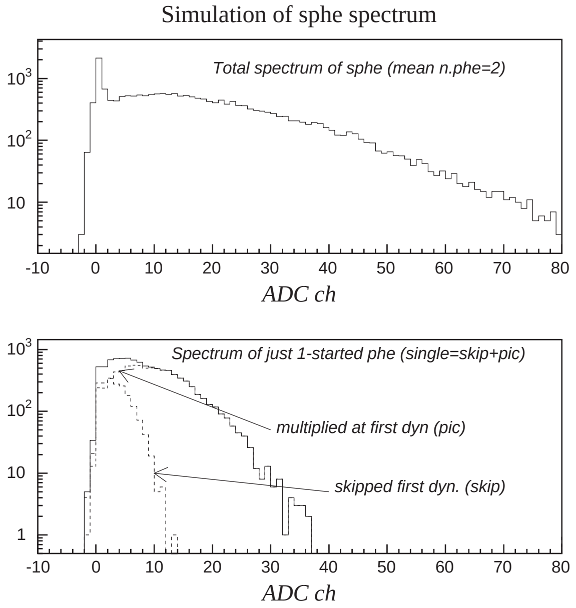

Fig. 4. Simulated sphe spectrum at 2000 V. At the top is the *total* spectrum, when a mean of 2 phe started from photocathode. At the bottom the basic *single* spectrum with its components superimposed: *skip* is due to electrons which skipped the first dynode and *pic* due to electrons which instead multiplied at first dynode (see Section 4).

[12], which triggered the acquisition of an ADC-module[2]).

The anode distribution obtained when just a single phe started from the cathode (the so-called *single* distribution), is the starting point of the sphe simulation, and is shown in the bottom of Fig. 4. The *single* distribution is strictly connected to the gain of the phototube, as will be described in Section 6. The anode distribution of two, three and more electrons is a supersposition of single distributions extracted by a Monte Carlo. Finally the *total* spectrum, which represents the "real" sphe distribution, is a poissonian sum over more than one phe (the low photo emission being a poissonian phenomenon), whose mean value μ can be given as an input to the program. More precisely, an "event" in the final total distribution is obtained by further including the typical pedestal and the channels smearing (the final number of electrons is translated in ADC-channels of our setup). Shown in the top of Fig. 4 is the total spectrum of a sphe simulated at 2000 V when a mean $\mu = 2$ photoelectrons started from the cathode. At the bottom, among the *single* events on which the *total* is based, one can also see the events whose electrons skipped the first dynode surface (thus missing the first stage of multiplication) owing to the transparency.

The conclusion is that the transparency degrades the single photoelectrons spectrum of a PM. As a result, the usual fitting functions are no longer adequate to describe such spectra and different solutions were investigated [13] (single photoelectron fine mesh spectra were found to be degraded in earlier studies [14]).

As already mentioned, the overall mean value of T was tuned to reproduce the gain at different HV. It is worthwhile underlining that T was tuned to also reproduce the total sphe spectra obtained in the laboratory. In fact, as one can see in Fig. 5, the model at $T = 0$ gives the typical "dimple" observed in non-fine mesh photomultipliers,

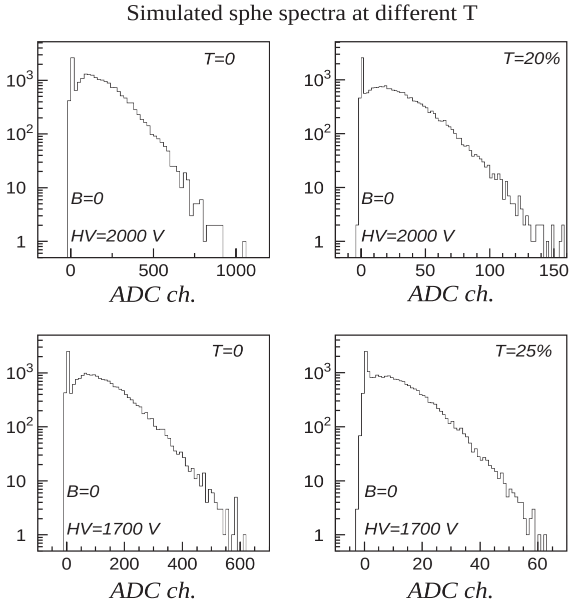

Fig. 5. Simulated sphe response at different T and $B = 0$. The peak of the single phe signal is well separated at zero transparency, but not at $T \sim 20\%$: the electrons which skipped the dynode do not multiply, resulting in a lower gain (as can be seen from ADCs on axis).

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[2] CAEN-mod 205 A.

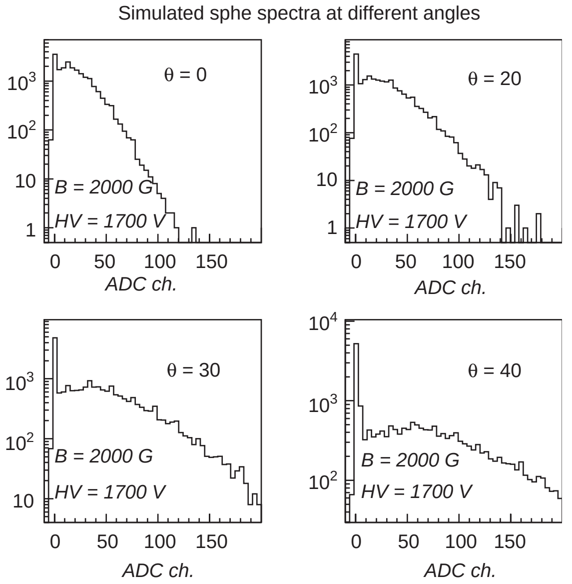

Fig. 6. Simulated sphe response at different angles θ, HV = 1700 V and $B = 2000$ G. As can be seen, the spectrum spread, together with the ‘sphe resolution’ (see the text), worsens notably as the angle increases (and this almost independently of the B-field magnitude).

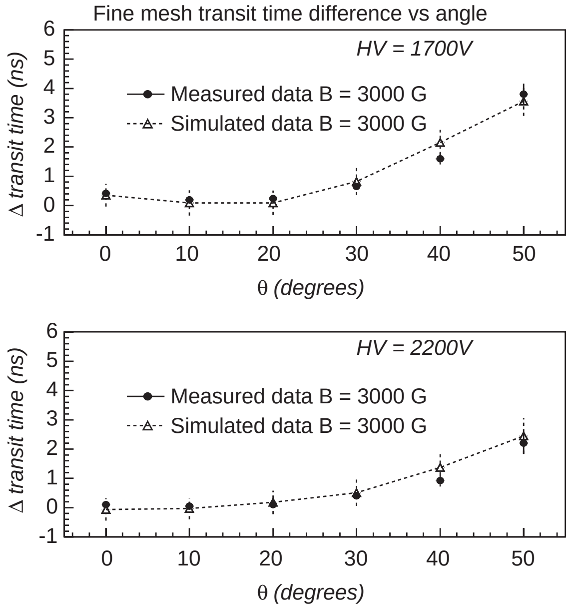

Fig. 7. Measured and simulated transit time difference ($t_{B>0} - t_{B=0}$), for two fine mesh photomultipliers in a magnetic field of 3000 G, as a function of the angle θ (see Section 5). High gain PM on top picture, low gain PM on bottom.

whereas for $T \sim 20\%$ the sphe experimental spectra shape for R5946 tubes is reproduced reasonably well [4].

Finally, the T parameter can reproduce the behavior of the sphe spectrum in a magnetic field and this is shown in Fig. 6: one effect of the magnetic field is that as θ increases more and more electrons are deflected outside the dynodes area and are lost. This tends to the degrading of the sphe resolution δ, which can be defined in the measurements, as the rms/mean of the anode distribution when approximately one phe started from the cathode. The simulated spectra are in agreement with the experimental ones [6] (and suggest that δ can barely be defined for the fine mesh in a magnetic field).

5. Time response in magnetic field

In the basic model of the simulation, the time for each electron in the avalanche as well as all its kinematical parameters can be recorded. In the data taken, the anode distribution of the transit time was compared for two PMs: one in the magnetic field and another outside. The “Δ transit time” measured as the difference in the arrival times recorded by the two PMs was thus investigated for various inclinations of the PM axis with respect to the field. In the simulation this transit time difference can be defined as the electron mean arrival time for $B \neq 0$ minus the electron mean arrival time for $B = 0$. In Fig. 7 the experimental data are compared with the simulated ones [5], for a low-gain and a high-gain phototube in a magnetic field of 3000 G and at different θ angles. From these plots, the conclusion is that the ‘Δ transit time’ worsens with the angle, in particular for PMs working at lower voltage (high-gain PM). Moreover, the transit time itself, at $B = 0$, is higher for the high-gain phototubes by a factor of about 2 ps/V and this was seen both from the data and the simulation [5].

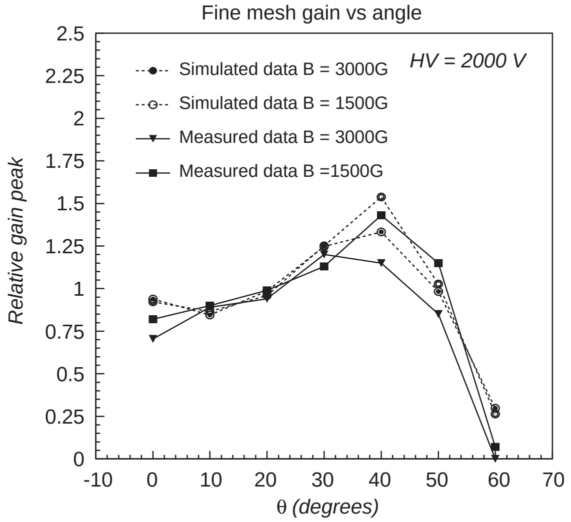

Fig. 8. Measured and simulated relative gain of fine mesh response $G(B\neq0)/G(B=0)$ at various angles θ and B fields. The data and the simulations show an increasing gain with the angle up to a value of almost 40°.

6. Fine mesh gain in magnetic field

From the simulated single photoelectron distribution (for the case for which just one phe is extracted from the cathode) it is possible to calculate the gain, which is, by definition, the number of final electrons at the anode. To the gain, we associated the mean value of the single simulated distribution. In this way, various gains were simulated with various B fields and various angles θ. The comparison of the results of the simulations with the measurements made[3] is exhibited in Fig. 8.

Both the data taken and the simulation results show that the fine mesh phototubes have a higher gain with the angle, up to a limit (almost 40°) after which the gain has an abrupt fall. This is almost independent of the intensity of the B field and of the PM characteristics [6].

From the fine mesh gain and the timing behavior in a magnetic field, studied both with simulations and laboratory measurements, a proper algorithm was developed in order to find the best arrangement of the calibrated PMs in the whole TOF-02 structure [16]. The higher θ-angle positions in the structure were occupied by the high gain PMs, so as to be able to increase their HV and reduce their timing degradation during the three years of data taking on ISS.

7. Conclusions

A complete fine mesh simulation has been shown. The basic model of the simulation and the way the avalanche of electrons is obtained have been described. The "transparency" parameter of the model has been investigated: it turns out to be around ~20% for a typical R5946 Hamamatsu working at 2000 V, and decreases at higher voltages and inclinations of electrons with respect to the dynode surface. The fine mesh single photelectron spectra have been simulated and reasonably reproduce the shapes obtained from the experimental data. The timing and gain characteristics of the fine mesh have been simulated, in a magnetic field and at various inclination θ of the PM axis with respect to the field. The simulation reproduced the experimental results quite well. The most critical value for the Time Of Flight of a space spectrometer is the transit time of the photomultipliers in a magnetic field, which has been shown to be more critical for PMs working at a lower voltage. For the TOF of AMS-02 the strategy has been to increase the HV of the fine meshes that are to be placed in the critical positions associated with highest angles between $\vec{B}$ and the PM axis.

References

[1] The AMS collaboration, Physics Reports, Vol. 366/6, August 2002, pp.331–404.
[2] L. Brocco, et al., The time of flight system of the AMS-02 space experiment, Proceedings of the Seventh ICATPP, Como, Italy, 2001.
[3] Hamamatsu Photonics, Photomultipler Tube R5946, 1994.
[4] C. Sbarra, A study of the behavior in magnetic field of fine mesh photomultipler (Hamamatsu R5946), for the TOF System of the AMS-02 Space Experiment, AMS-BO International Note, 2001.

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[3] The gain scale factor $1/(1+\delta^2)$ [12] was chosen to reproduce the nominal gain given by Hamamatsu sheet.

[5] L. Brocco, et al., Behavior in strong magnetic field of the photomultipliers for the TOF system of the AMS-02 space experiment, Proceedings of the 27th ICRC, 2001.
[6] G. Levi, et al., Simulation of the fine mesh photomultipliers for the TOF of AMS-02, Proceedings of the Eighth ICATPP, Como, Italy, 2003.
[7] G. Barbiellini, et al., Nucl. Instr. and Meth. A 362 (1995) 245.
[8] R. Chechik, et al., WIS-93/63/Jul-PH, 1993.
[9] H. Bruining, Physics and Applications of Secondary Electron Emission, Pergamon Press, Oxford, 1954.
[10] I. Chirikov-Zorin, et al., Nucl. Instr. and Meth. A 456 (2000) 310.
[11] Philips Photonics, Photomultiplier Tubes Principles and Applications, 1994.
[12] B. Bencheick, et al., Nucl. Instr. and Meth. A 315 (1992) 349.
[13] C. Sbarra, Comparison between fit functions of simulated single phe spectra, AMS-BO International Note, 2003.
[14] R. Enomoto, et al., Nucl. Instr. and Meth. A 332 (1993) 129.
[15] R. Suda, et al., Nucl. Instr. and Meth. A 406 (1998) 213.
[16] L. Amati, et al., Algoritmo genetico per l'ottimizzazione dei fotomoltiplicatori del TOF di AMS-02, Presented at the LXXXIX SIF, Parma, Italy, 2003.

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