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Behavior in strong magnetic field of the photomultiplers for the TOF system of the AMS-02 space experiment

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Abstract. Some Hamamatsu R5946 photomultiplier tubes have been tested in magnetic field, in view of their use in the TOF system of AMS-02 experiment, a cosmic ray spectrometer to be operated in space after 2003. The PMTs are shown to be rather insensitive to the magnetic field up to about $4\,\mathrm{kG}$ at angles between the field direction and tube axis up to about $30°$. A comparison with simulation results is also presented.

1 Introduction

The *Alpha Magnetic Spectrometer* (AMS) (Ahlen et al., 1994) is the large acceptance ($0.65\,\mathrm{m}^2$) particle detector that will be installed on the International Space Station at the end of 2003, and will measure cosmic ray fluxes for at least three years in a low orbit (about 400 km) around the heart. The AMS experiment will address two fundamental questions in astroparticle physics: the possible presence of cosmological antimatter in the universe and the nature of the so-called "dark matter". These physics goals require the measurement of particle momentum, velocity and charge with the highest degree of confidence as possible and extremely accurate particle identification.

After the successful operation aboard of the Space Shuttle Discovery in a 10-days test flight carried out in June 1998 (J.Alcaraz et al., 2000), the detector has been redesigned to increase the maximum detectable rigidity up to 1 TV, by using a superconducting magnet which will provide a maximum field of about $0.8\,\mathrm{T}$[1]. As a consequence, the TOF system (S. Alvisi et al., 1999) had also to be redesigned to operate in a stronger magnetic field and with different values for the angle between the photomultiplier tubes and the field direction.

In the following a short description of the new TOF system is given and results are reported on the operation of the Hamamatsu R5946 photomultiplier tubes inside a magnetic field. The results of our first approach simulation are also reported.

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[1]The improved detector is nicknamed AMS-02 in the following.

2 The TOF system of AMS-02

The TOF system, to be designed and built at the INFN Laboratories in Bologna, will provide:

1. the fast trigger of the experiment;

2. the measurement of the time of flight of the particles traversing the detector with a resolution sufficient to distinguish upwards and downwards going particles at a level of at least 10^{-10}, and electron and antiproton up to about 2 GeV.

In the test flight of June 1998, Hamamatsu R5900 tubes were used to detect the scintillation light from the TOF counters because they provided small occupancy, low power consumption and good time resolution. In order to shield the tubes from the residual magnetic field ($200\,\mathrm{G}$) the PMs were enclosed in a $0.5\,\mathrm{mm}$ thick shielding case made of vacoflux permalloy.

The AMS-02 superconducting magnet produces a much larger field (about $2\div3\,\mathrm{kG}$), of variable direction on the TOF planes. Figure 1 shows the magnetic field magnitude and angle versus the vertical (z) direction at the vertical coordinates where the TOF planes are positioned. The TOF photomultiplers must withstand the magnetic field witout shielding, in a large interval of angles with respect to the field direction.

The mechanical constraints of the AMS-02 apparatus do not allow to optimize completely the tube orientation. The field magnitude and the angle between the magnetic field and the tube axis are shown in figure 2 for all tubes of the system.

After a market study, the Hamamatsu R5946 photomultiplier tube was considered the best choice and throughfully tested for time resolution and pulse height response in magnetic field.

3 Experimental PM behavior in magnetic field

In order to investigate the PM response in different conditions, the tube was placed inside the poles of an electromagnet (maximum field $4\,\mathrm{kG}$) on a movable stand which could be rotated at a maximum angle of $90°$ with respect to the magnetic field. The light was produced by a red diode and guided to the photomultiplier tube by two optical fibres. The charge signal from the photomultiplier was digitized by an ADC and registered by a PC-based data acquisition system.

3.1 PM gain and single photoelectron response

The photomultiplier tubes gain has been measured following the method suggested by B. Bencheick et al. (1992).

Three tubes were selected for testing in magnetic field: one with high gain (PM R5946-WA9386), one with intermediate gain (PM R5946-WA9385) and one with low gain (PM R5946-WA9381). All three tubes were then operated at a gain of about 2×10^6, with voltages of $-1700\,\mathrm{V}$, $-2000\,\mathrm{V}$ and $-2200\,\mathrm{V}$, respectively.

The photomultiplier responses have been measured for various intensities of the magnetic field B and with different angles between the tube axis and the field direction, called θ in the following. Figure 3 shows the response of the tubes at different values of the magnetic field, normalized to that at $B = 0$, as a function of θ. For $\theta \leq 50°$, the relative response is well above 50% up to the highest values of B. Only at $\theta = 60°$ the response goes to zero for $B \geq 1000\,\mathrm{G}$.

The single photoelectron resolution[2] has been measured using a very low-level light pulse from the LED for several tube orientations and field magnitudes. It degrades rapidly with increasing magnetic field at large angles and with increasing angle at fixed magnetic field (L. Patuelli, 2000).

The consequence of the worsening of the single photoelectron response with increasing field and θ is a small degradation in the resolution of the energy measurement.

No relevant difference has been seen between the three tubes.

3.2 Time resolution

Although the test system has not been designed for a very precise measurement of the time resolution of the photomultiplier tubes, some conclusions on the effect of the magnetic field can nonetheless be drawn, as explained in the following.

The signal from the photomultiplier tube has been sent to a discriminator (with the threshold set at $30\,\mathrm{mV}$) and then to the stop of a $50\,\mathrm{ps}$/bin TDC, started by the pulse driving the LED. The resulting time distribution has a resolution of about $330\,\mathrm{ps}$, much worse than the $100\,\mathrm{ps}$ expected for real scintillation light because of the rather longer duration of the LED light pulse. In fig. 4 are shown the mean transit times[3] and the time resolutions for tubes no. 9381 and 9386 , as function of the magnetic field and for different values of θ (the times plotted are relative to the time at $B = 0$ of PM9381).

[2] $\delta = \sigma_{peak}/\mathrm{peak}$ (B. Bencheick et al., 1992)

[3] transit time: time delay with respect to the LED pulse.

The most relevant observation is that the tube operated at higher voltage (no.9381) shows a shorter transit time and a better time resolution. The transit time generally gets worse with encreasing angle for both PMTs, but it is more critical for the high gain PM (no.9386). This is also confirmed by our simulation, and gives us some hints on the possible way of arranging the PMTs in the new TOF system of AMS-02. Moreover a strong correlation is observed between time resolution and transit time for both tubes.

4 Simulation of time response in magnetic field

We simulated the fine mesh behaviour by solving the photoelectron first order differential equation of motion (in the velocity and position unknowns). We used the Runge-Kutta numerical approximate solution in finite time intervals (W. Hpress et al., 2000).

We started with many photoelectrons from the fine mesh photocatode, and followed them up to the first dynode, considering the electric and magnetic field strengts and the angle between them.

To simulate the fine mesh time response, we decided to extract randomly only one secondary electron at each dynode, up to the final anode. The photoelectron extracted was given an angular distribution generally flat over the downwards emisphere (i.e. towards the anode). The only case in which such secondary electron kept the ingoing direction, was when it went elastically scattered.

We followed the energy distribution of the secondary electrons emitted (SEE), whose general shape is given also in G. Barbiellini et al. (1995). In particular, we 'enhanced' the elastic peak of the SEE distribution (becouse of the 'holed' geometry of the fine mesh dynodes).

Finally, we chose one of the secondary electrons emitted at each dynode, and cumulated the time it took to get to the next one, up to the anode. At the end, we got a distribution of time of arrivals at the anode as a function of θ and magnetic field strenght, for different simulated HV.

Figure 5 shows our simulation of the fine mesh time response and the experimental results as function of the angle between $\mathbf{E}$ and $\mathbf{B}$ and at different magnetic field strenghts for PM no.9386 (HV= 1700) and for the PM no.9381 (HV= 2200 V). The time plotted is relative to the time at $B = 0$ of the low gain PM.

The worsening of the transit time with respect to the angle θ, both experimental than simulated, is most critical for the highest gain fine mesh PM (no.9386). This is true also for the dispersion of the measured time distributions, see figure 4 (L. Patuelli, 2000).

5 Conclusions

The results presented in this paper indicate that the Hamamatsu R5946 photomultiplier tubes do not show a significant decrease in gain when operated inside high magnetic field regions ($B \sim 4\,\mathrm{kG}$) up to quite large angles between the tube axis and the field direction ($\theta \leq 50°$).

A serious worsening of the single photoelectron response and of the time resolution occurs when the tube is operated at angles above $30°$, nearly independently of the applied magnetic field.

The effect of the worsening of the single photoelectron response is not very relevant on the energy resolution of the AMS-02 TOF system, but in order to reduce as much as possible the time resolution worsening, we had to constrain the mechanical design of the TOF so to avoid the larger angles between tube axis and field direction ($\theta \gtrsim 30°$).

Nevertheless, the data combined with the simulation results, suggest us also to use PM with low gain for the critical cases in which they must yeld an angle θ greater that $30°$, so to limit the AMS-02 TOF photomultipler timing degradation due to higher magnetic field working conditions.

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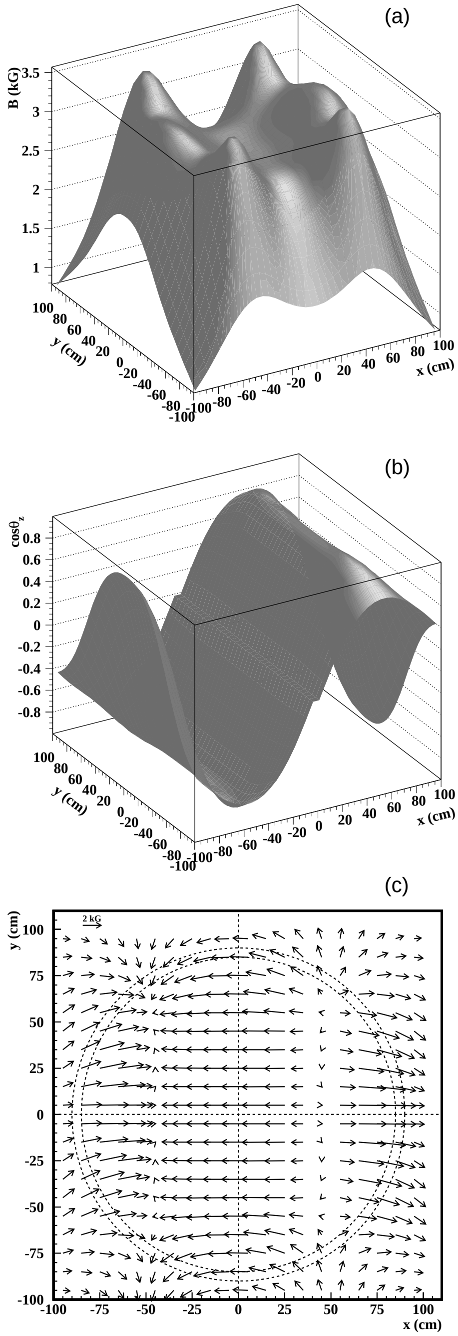

Fig. 1. The magnetic field magnitude (a), direction w.r.t. the z axis (b), and the component in the plane at $z = 60\,\mathrm{cm}$. The dashed circles in (c) represent the approximate position position of the photomultipler tubes.

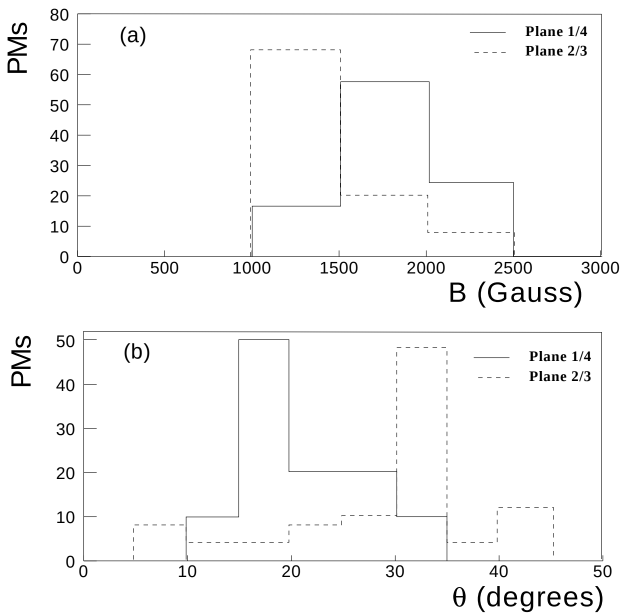

Fig. 2. Magnetic field intensity (a) and angle (b) distribution for PMTs of plane 1 (solid line) and 4 (dashed line)

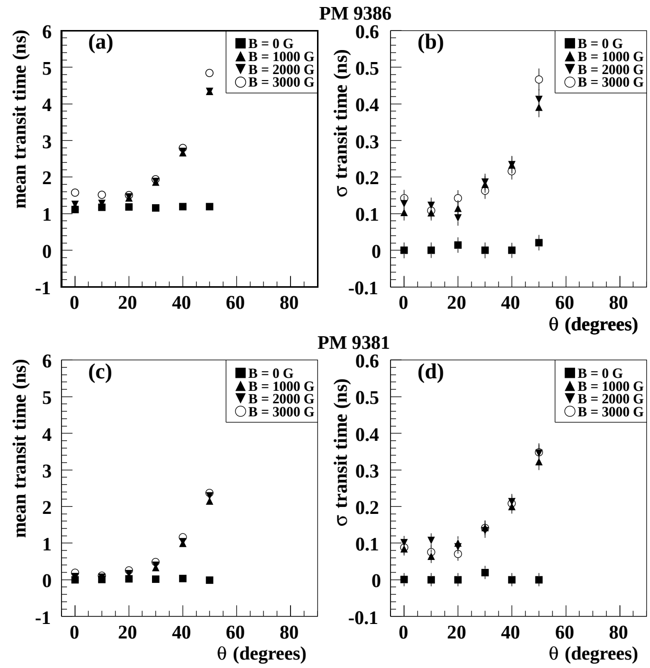

Fig. 4. Time delay with respect to LED pulse ("mean transit time") and time resolution as function of θ and for different values of B, for PM no. 9386 (a,b) (HV=1700V) and PM n.9381 (c,d) (HV=2200V). For both PM the time at $B = 0$ of PM9381 is subtracted. The PM operated at higher voltage shows the shorter transit time and the best time resolution.

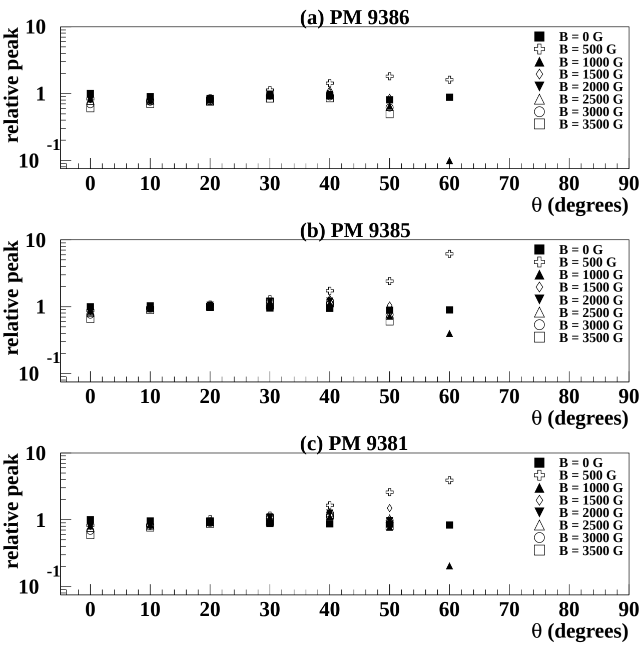

Fig. 3. PMTs behavior as function of the θ angle between the tube axis and the field direction, for different values of the magnetic field B (normalized to $B = 0$).

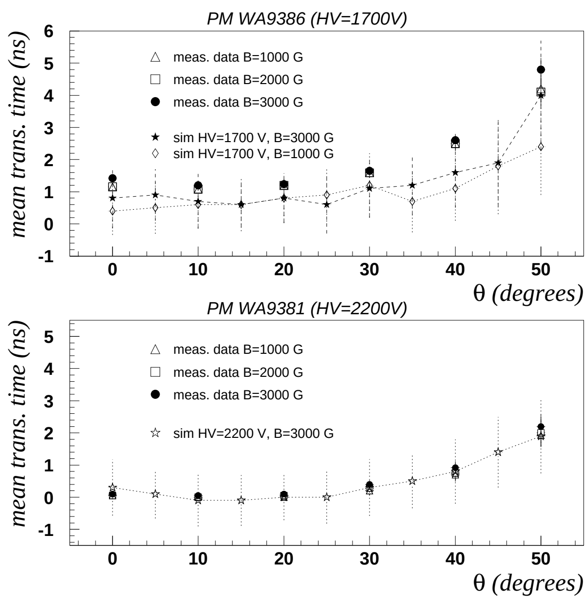

Fig. 5. Measured and simulated mean transit time for the PM9386 (HV=1700) and for the PM9381 (HV=2200) at various θ and fields (the time at $B = 0$ of low gain PM is subtracted). The PM working at higher voltage shows a shorter transit time also in such simulation.