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The Isotope Matter-Antimatter Experiment Time-of-Flight System

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ABSTRACT

A state-of-the-art time-of-flight (TOF) system has been developed for measuring particle velocities in the Isotope Matter-Antimatter Experiment (IMAX), a balloon-borne magnetic-rigidity spectrometer designed to measure the abundances and spectra of antiprotons and light isotopes in the cosmic radiation. Preliminary time-of-flight resolutions of 130 ps for protons and 105 ps for helium have been obtained. A description of the TOF system and an initial evaluation of its flight performance are presented.

1. INTRODUCTION

IMAX (Mitchell *et al.*, 1993) was designed to measure cosmic ray antiprotons and the isotopes of hydrogen and helium, over an energy range from about 200 MeV/nucleon to 3 GeV/nucleon. IMAX measures the velocity of incident particles in order to identify particle backgrounds to the antiproton measurements, and for isotopic mass identification. To meet the IMAX science goals, the TOF system was required to have a flight time resolution of at least 200 ps for singly charged particles, comparable to the resolution of the TOF systems in previous balloon-borne magnetic spectrometer experiments such as: PBAR (Tomasch *et al.*, 1990), LEAP (Streitmatter *et al.*, 1989), and SMILI (Beatty *et al.*, 1993). It was required that this performance be achieved with about half the total scintillator thickness used in previous systems, to reduce both the overall weight of the TOF system and the amount of matter in the path of incident particles.

2. DESCRIPTION

The IMAX TOF system consists of three 60 cm x 20 cm x 1 cm Bicron BC-420 scintillator paddles located at the top of the instrument and three paddles at the bottom, separated by a flight path of 2.5 m. Each paddle is viewed by two Hamamatsu R2083 8-stage photomultiplier tubes (PMT), coupled to the scintillator through twisted light-pipes of ultra-violet transmitting (UVT) acrylic plastic. Each light-pipe has four 5 cm wide segments with a final machined length of 24 cm. The light-pipes terminate in UVT acrylic reducer/adapters which match the end area of the light-pipes to the 16.6 cm^2 photocathode area of the PMTs. The adapters have a 7 cm conical reducer section with an side angle of 10°, ending in a 3 cm by 4.6 cm diameter cylindrical section which allows the PMT to be recessed within a magnetic shield.

The dimensions and configuration of the light-pipes were dictated, in part, by the cylindrical gondola of the NASA/NMSU Balloon-Borne Magnet Facility. The light-pipes on the four paddles nearest the magnet are bent up at 55° with a variation in segment length of less than 2 mm. The remaining light-pipes are bent up at 65° and back toward the magnet at 25° with 5 mm variations in segment length. In order to maximize light transmission, the radii of curvature of the bends and twists are at least eight times the segment thickness. The surfaces of the light-pipes are highly polished so as to reduce light loss from internal reflection.

Except for the adapters, the scintillators and light-pipes are wrapped in light-absorbing black paper to insure that photons which leave the scintillator or light-pipes are unlikely to re-enter. This eliminates photon paths outside the plastic and reduces the probability that photons which undergo a large number of bounces will reach the PMTs (d' Agostini *et al.*, 1981 and 1984). These comprise a tail to the photon time-distribution at the PMT which increases the total charge digitized by the charge-integrating ADC but carries no information on the leading edge of the output pulse. Compensating for the amplitude-dependent time-walk in leading-edge timing based on the integrated charge depends on a correspondence between total charge and leading-edge amplitude. Eliminating photons with long flight paths in the scintillator can improve the time-walk corrections by improving this correspondence. The light-absorbing wrappings slightly reduce the energy resolution of the scintillator since less total light is collected. The adapter/reducers were wrapped in aluminum foil except for the final cylinder, which was wrapped in Millipore filter paper to provide electrical insulation for the photocathode.

The scintillators, light-pipes, and reducers were joined with Hartel HE 17017 polyurethane glue. The PMTs were attached with GE RTV 615 silicone glue to allow removal. The TOF scintillators were assembled in April, 1991 and showed no degradation in optical performance in July, 1992, when IMAX was flown.

The R2083 PMTs were operated at negative high-voltage, typically 2700 to 3000 V. The PMT bases were designed for high reliability and optimum fast-pulse performance, employing G-10 glass-epoxy circuit boards laid out so that the lead lengths between the charge-storage capacitors and the dynodes were minimized. Military specification (RN60D and RN55D) metal-film resistors and Z5U ceramic capacitors were used throughout. The PMT anode outputs were coupled directly to 50 Ω coaxial cables. The capacitors and dynodes were connected by damping resistors to eliminate ringing from parasitic inductance.

The PMTs were surrounded by multilayer magnetic shields customized to match the ambient magnetic fields: 50 to 65 gauss at the top and 200 to 280 gauss at the bottom. The inner shield used four layers of 0.004" Perfection Mica CO-NETIC AA high-μ foil extending 5 cm beyond the photocathode. Each foil layer was overlapped on itself and was separated from the next layer by PVC tape. The overlap regions were rotated by 90° in each successive layer. The foil was surrounded by a 0.025" layer of CO-NETIC B separated from the inner shield by an electrically insulating layer about 1/8" in thickness. The bottom PMTs also used a 0.125" thick low-carbon (1010) steel outer shield. At full field, no reduction in PMT gain or resolution was discernable.

In order to insure that the PMT photocathodes were not near a ground plane, the inner magnetic shields were tied (through 1 MΩ resistors) to negative high-voltage. The outer shields were grounded.

To preserve pulse shapes, the PMT signals were carried on 5 m RG-58 coaxial cables and split differentially between discriminators, ADCs, and a dark-matter experiment (McGuire and Bowen, 1993). The electronics used were LeCroy 2213 discriminators, 2229 (Mod 400) TDCs and 2249A ADCs. The discriminator thresholds were set at 15 mV, and the pulse from a minimum ionizing particle was typically above 100 mV.

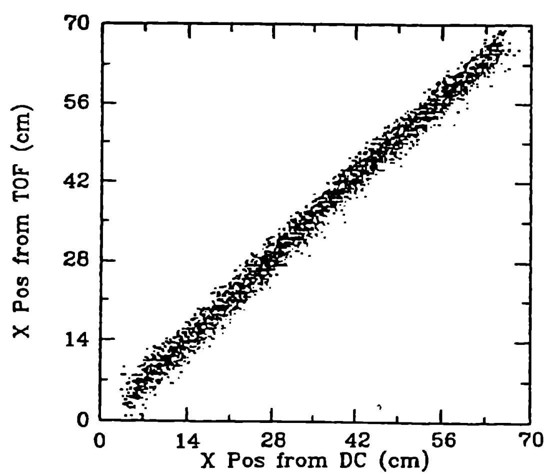

FIGURE 1: Calculated position from timing vs. incident position from particle trajectory.

3. RESOLUTION

To first order, the time measured at the PMTs is a linear function of incident position, characterized by an effective velocity (v_{eff}) for light propagation in the paddle. This v_{eff} depends on the details of the paddle and light-pipes and on the mean number of photons necessary to produce a PMT output signal greater than the discriminator threshold. The v_{eff} can be derived from a fit to the difference in times measured at the ends of a paddle as a function of incident position. Figure 1, from ground level muon data, shows position derived from the measured times and the fitted v_{eff} versus position obtained from the particle trajectory measured by the drift chambers. Small deviations from linearity are visible.

Analysis of the performance of the TOF system is at a preliminary stage at the time of submission. The final analysis will take into account the full dependence on the positions at which each incident particle struck the scintillators, the length of the particle flight-path, and the amplitude-dependent timing walk from leading-edge discrimination. Currently, the flight time for a particle is taken to be the average time measured by the PMTs on a bottom paddle minus the average time measured on a top paddle with cosine corrections for the flight path. Using average times is equivalent to correcting for the linear position dependence.

The distribution of flight times measured for ground level muons with the magnetic field off has σ=148 ps. By comparison, σ=185 ps for Z=1, β=1 was reported for the PBAR TOF system (Tomasch, *et al.* 1990) with full amplitude and position corrections. Without amplitude corrections, the PBAR TOF gave σ=240 ps in lab. tests with ground level muons (Lowder, 1988).

More representative of the performance of the IMAX TOF, over the energy range where it will supply the primary velocity measurement, is the timing distribution for flight proton data, shown in Figure 2. For these data, σ=130 ps. This is better than the ground muon result because more photons are produced by the lower velocity protons. However, in the magnetic field, particle trajectories have substantial curvature at lower rigidities. Correction for the actual flight path may improve the resolution considerably.

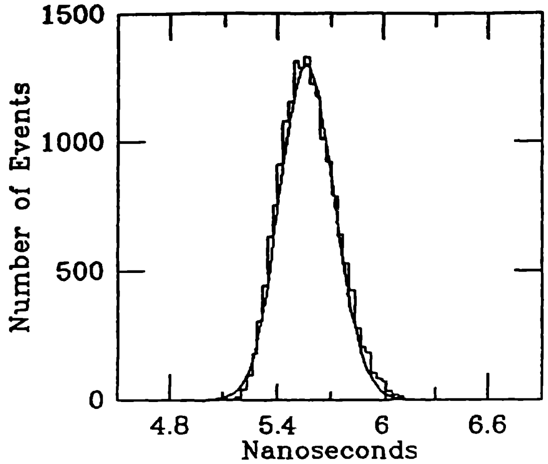

FIGURE 2: TOF from flight proton data σ=130 ps

About four times as many photons are produced for an incident helium as for a proton of equal MeV/nucleon. Since the timing resolution (to the point where the electronic contribution becomes important) should be proportional to the inverse square root of the number of photoelectrons, the resolution for helium should be almost half the resolution for protons. However, the flight data for $Z \geq 2$ has σ=105 ps, reflecting non-statistical broadening. Since this would affect the proton results as well, the magnitude of the broadening can be estimated by assuming that the proton and helium results are both degraded from their intrinsic values by a common factor

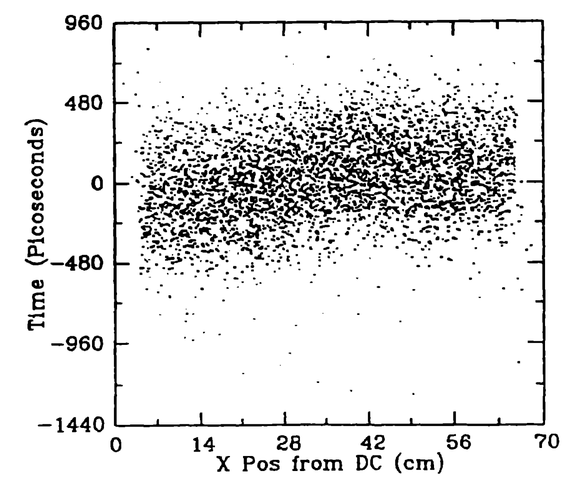

FIGURE 3: Non-linear position dependence.

added in quadrature. If the intrinsic helium timing resolution is half that for protons, the common factor is on the order of 90 ps. This suggests that with full corrections, the final resolution (including a conservative factor for electronic and tracking contributions) may approach 100 ps for protons and 65 ps for helium.

Some of the broadening can be attributed to second-order position dependence, illustrated in Figure 3 which shows the timing data which went into Figure 1, corrected for position using the fitted v_{eff}.

4. COMPARISON TO PREVIOUS FLIGHT EXPERIMENTS

The IMAX time-of-flight system has already demonstrated excellent performance. For comparison, PBAR used 2.54 cm thick scintillators to achieve a resolution of 160-185 ps (depending on β) for Z=1 particles and less than 100 ps for helium at low β. LEAP (Stochaj, 1990) had two independent 1 cm scintillators in each layer and obtained 200-270 ps for Z=1 particles. SMILI achieved a resolution of 90-150 ps (depending on β) for helium using 2 cm paddles. It should be noted that different methods were used to obtain the resolutions quoted for these experiments so some care must be used in making direct comparisons.

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