

MEASUREMENT OF TRAPPED PROTON FLUENCES IN MAIN STACK OF P0006 EXPERIMENT*

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SUMMARY

We have measured directional distribution and Eastward directed mission fluence of trapped protons at two different energies with plastic nuclear track detectors (CR-39 with DOP) in the main stack of the P0006 experiment on LDEF. Results show arriving directions of trapped protons have very high anisotropy with most protons arriving from the West direction. Selecting these particles we have determined the mission fluence of Eastward directed trapped protons. We found experimental fluences are slightly higher than results of the model calculations of Armstrong and Colborn.

INTRODUCTION

The Long Duration Exposure Facility (LDEF) was flown in space for almost six years in low Earth orbit and low inclination. Pre-recovery estimates show that 95% of the charge particle exposure for the LDEF orbit is from trapped protons[1]. Almost all proton fluence was accumulated in the South Atlantic Anomaly (SAA).

The trapped proton fluence in the SAA is highly anisotropic. This anisotropy has not been an important practical consideration for most previous missions because the varying spacecraft attitude during passage through the radiation belt averages out anisotropy effects over many orbits. However, for the fixed orientation of LDEF and for other planned missions (e.g. space station), where the spacecraft will be gravity-gradient stabilized, the cumulative proton exposure will remain anisotropic, and will result in a highly non-uniform dose distribution around the spacecraft.

The current theoretical models describing the proton radiation environment have a large uncertainty[2] and therefore their experimental verification is of great importance.

In the present paper, we introduce experimental data of measurement, directional distribution and mission fluence of Eastward directed trapped protons using plastic nuclear track detectors (PNTDs) included in the P0006 experiment flown on LDEF.

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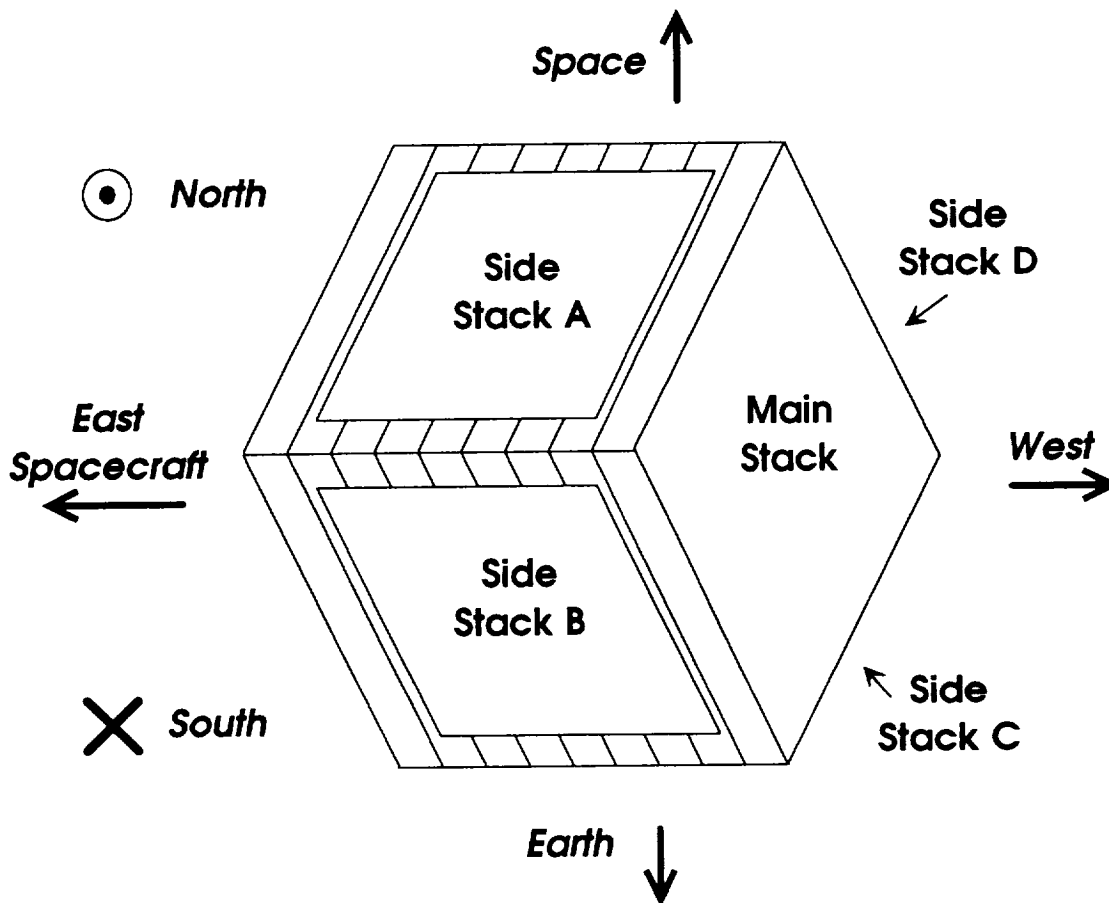


Figure 1: Block scheme of the P0006 experiment on LDEF. Measurements were made in the main stack at 0.6 and 9.5 g/cm² shielding depths at the center of the CR-39 (DOP) plastic nuclear detector sheets.

EXPERIMENT

The P0006 experiment was located in the F2 tray of the LDEF satellite. It consisted of one main and four side stacks of plastic nuclear track detectors as shown in Figure 1. In previous experiments we have measured total track density[3] and linear energy transfer (LET) spectra[4] in these stacks. These measurements indirectly confirmed the existence of proton fluence directionality and defined it as being nearly normal to the main stack of the P0006 experiment. The orientation of side stacks (and the main stack) was determined by finding the best agreement between experimental and expected directional dependent effects.

In the present experiment, directional distribution and mission fluence of protons were measured directly with PNTDs (CR-39 with DOP). CR-39 is a threshold detector and for etching conditions of the current experiment, it can detect protons only close to their stopping points. The trapped protons of different energies passing through detector layers will stop at different depths in the stack in accordance

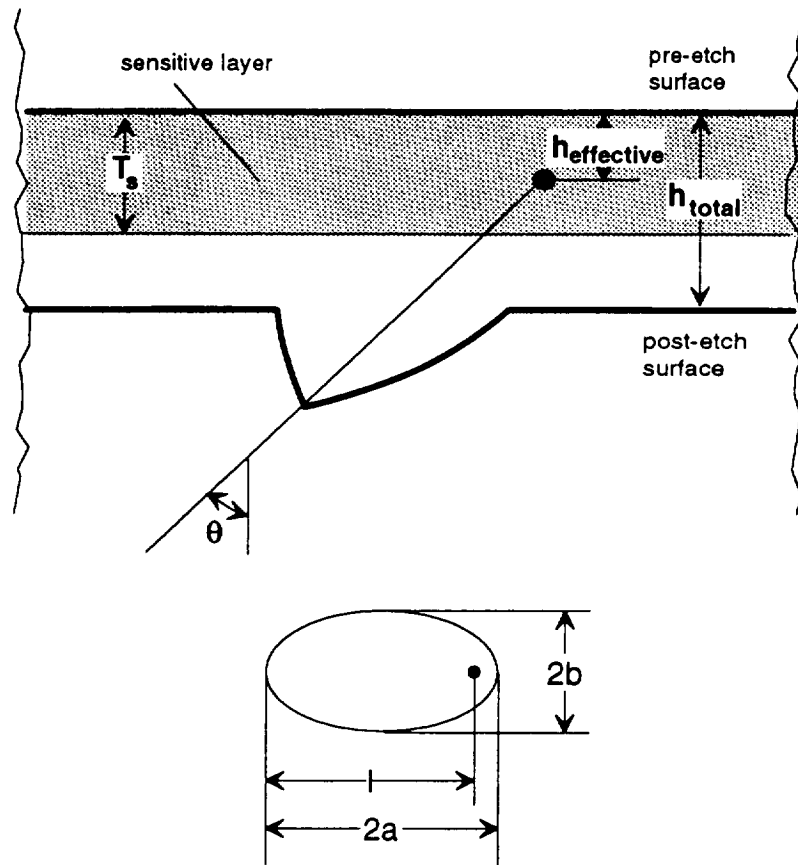


Figure 2: The measurable parameters of an etched track formed by a proton which stopped in the sensitive layer near the bottom surface of the detector.

with the values of their ranges. Measuring the stopping proton density in certain sensitive detector layers makes it possible to obtain the differential energy fluence of protons with energy E in the energy interval ΔE , where E is defined by the matter thickness above the considered detector layer and ΔE is defined by the thickness of the sensitive layer.

CR-39 with DOP under 0.6 and 9.5 g/cm² shielding depths were chosen for measurements. The detectors were processed for 36 hours in 6.25 N NaOH solution at 50°C. Measurements were made at the center of the detectors using the double layer track anti-coincidence method. After etching, two adjacent layers of CR-39 were reassembled into their flight configuration relative to one another on the microscope stage. A particle event was selected for measurement when a pointed (non-rounded) etched track was produced on the bottom surface of the top layer and no corresponding track was found on the top surface of the bottom layer. The major a and minor b axes of the track opening and the distance between the “back” of the track opening and its tip l were measured (Figure 2) using a videomicrometer.

We supposed all tracks chosen by the above procedure were produced by stopping protons. Tracks of heavy recoil particles are overetched and rounded, and the contribution of heavier primary elements is negligible.

A proton track of the selected type can be described by two parameters: dip angle δ , the angle between the particle trajectory and the detector surface, and the effective removed layer h , the distance between the particle stopping point and the post-etch surface (Figure 2). To obtain these parameters from the etched track size measurements, we used the theory of track development kinetics[5]. First we tried to use the constant etch rate ratio approximation[6] but it provided spurious results. This is not surprising since, near the stopping point of the particles, LET and the directly proportional etch rate ratio along the particle trajectory changes rapidly. Hence we used a variable etch rate ratio model. The form of the detector response curve was chosen to be:

$$V = 1 + A \text{REL}_{200}^B, \quad (1)$$

where REL_{200} is the restricted energy loss rate; A and B are parameters. Using equation (1) and the theory of etched track development, the minor and major axes and the l distance were calculated as a function of the dip angle and effective removed layer. From comparison of calculated and measured track sizes, the dip angle and the effective removed layer were determined for each particle.

In order to be detected, the proton has to stop in some sensitive layer thickness T_s of the detector (Figure 2). T_s is a function of the track size selection criteria. In our experiment we can effectively detect only tracks with sizes greater than $2 \mu\text{m}$. Through the detector response function (1) and the theory of track development, this value defines the upper boundary surface of the sensitive layer. Particles which stop above this surface have tracks which are too small to be detected.

Since the sensitive layer is very thin in a small scanning area, the volume density of stopping protons should be uniform. This means that the distribution of the experimental effective removed layers should also be uniform. We used this criterion to find the best values of the A and B parameters in the (1) detector response curve. Figure 3 shows three examples of distribution of effective removed layers using different sets of A and B values. Since the maximum effective removed layer was $9 \mu\text{m}$ in our case, curve No. 2 was chosen in Figure 3, and the thickness of the sensitive layer was determined to be $4 \mu\text{m}$.

RESULTS AND DISCUSSION

The polar angle is defined as the angle between the particle trajectory and the normal of the detector surface in the main stack of the P0006 experiment. Tracks with polar angles $\theta \leq 30^\circ$ ($\delta \geq 60^\circ$) were selected for further analysis. This choice was determined in order to minimize the effect of scanning inefficiency at higher polar angles. Altogether 269 and 300 tracks were selected in layers which were located at main stack depths of 0.6 and 9.6 g/cm^2 , respectively.

The arriving directions of stopping protons are presented in Figures 4 and 5. It can be seen that the preferred directionality of the arriving protons is not normal to the main stack. Both distributions have a maximum at polar angles of about 20° and at an azimuthal angle which corresponds to the West direction.

To assess the eastward directed trapped proton fluences, we chose the track in the highest density quadrants around the west direction in Figures 4 and 5. 185 and 139 tracks were found in these quadrants

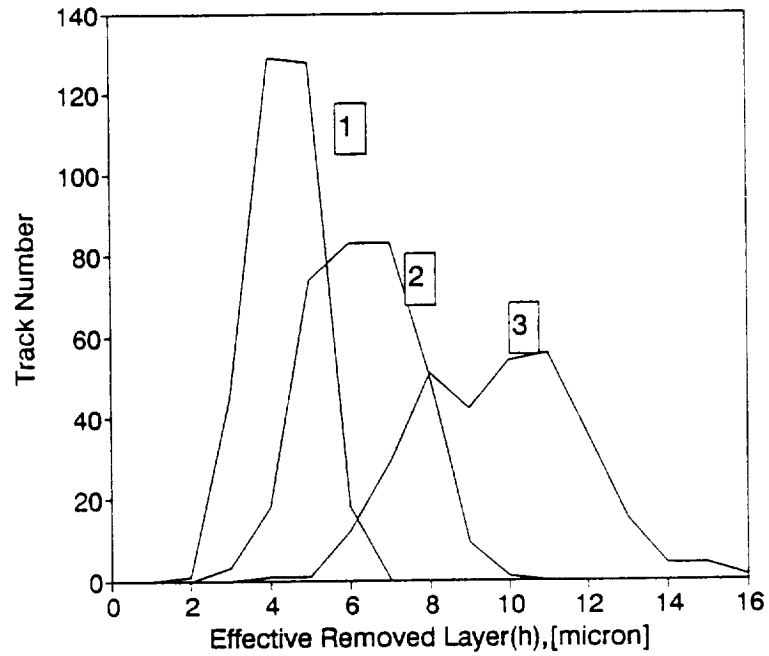


Figure 3: Distributions of calculated effective removed layers using different detector response functions: 1) $V = 1 + REL^{1.4}/162$, 2) $V = 1 + REL/100$, and 3) $V = 1 + REL^{1.1}/432$.

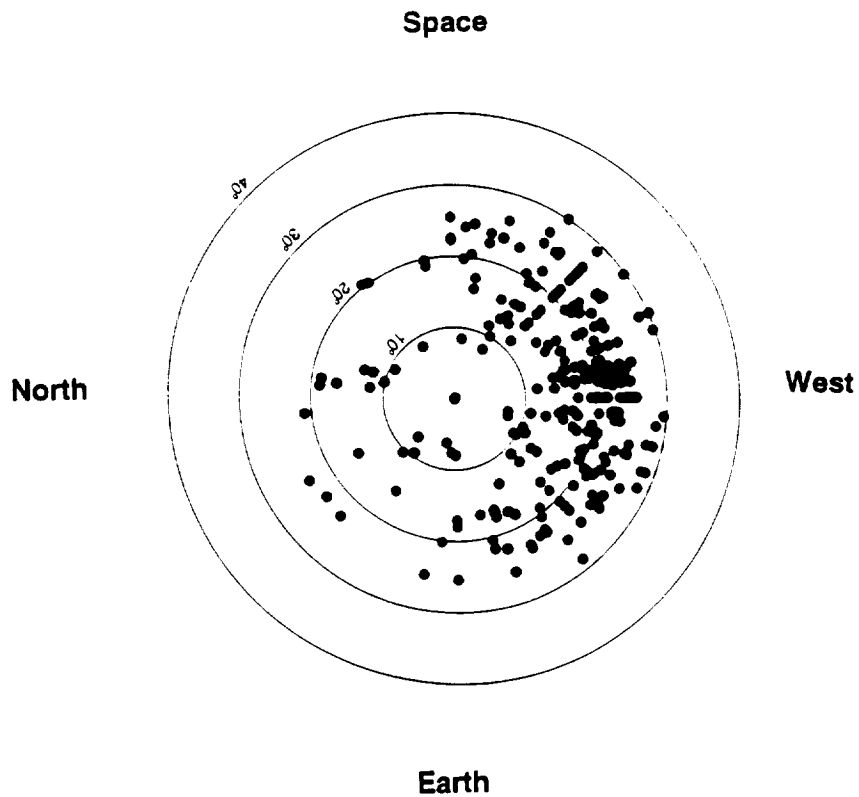


Figure 4: Distribution of arriving directions of stopping protons at 0.6 g/cm^2 .

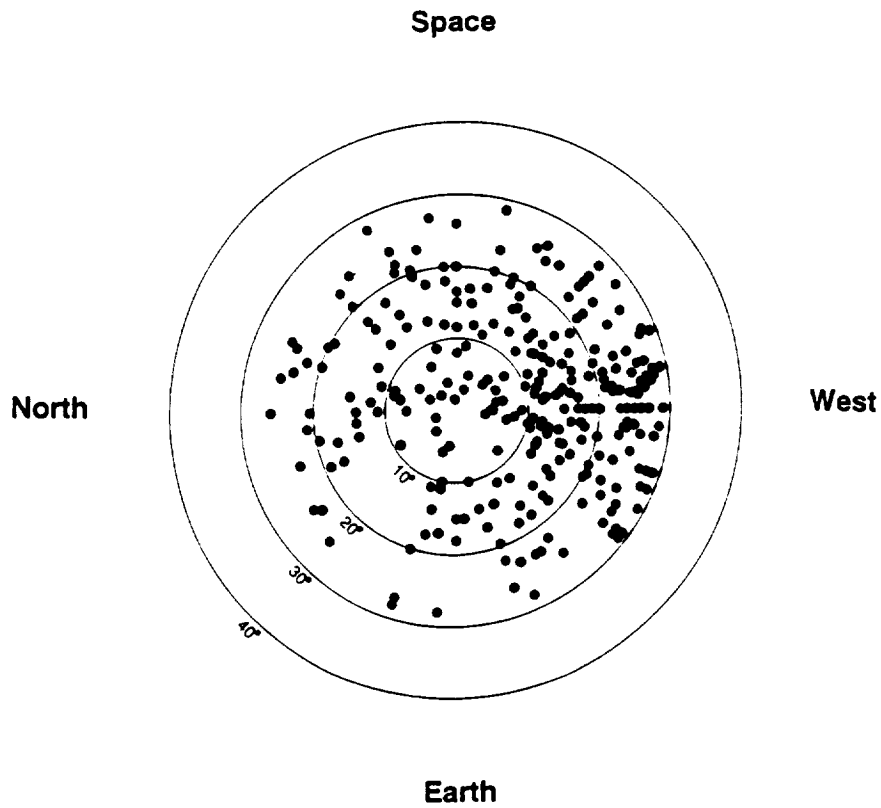


Figure 5: Distribution of arriving directions of stopping protons at 9.5 g/cm^2 .

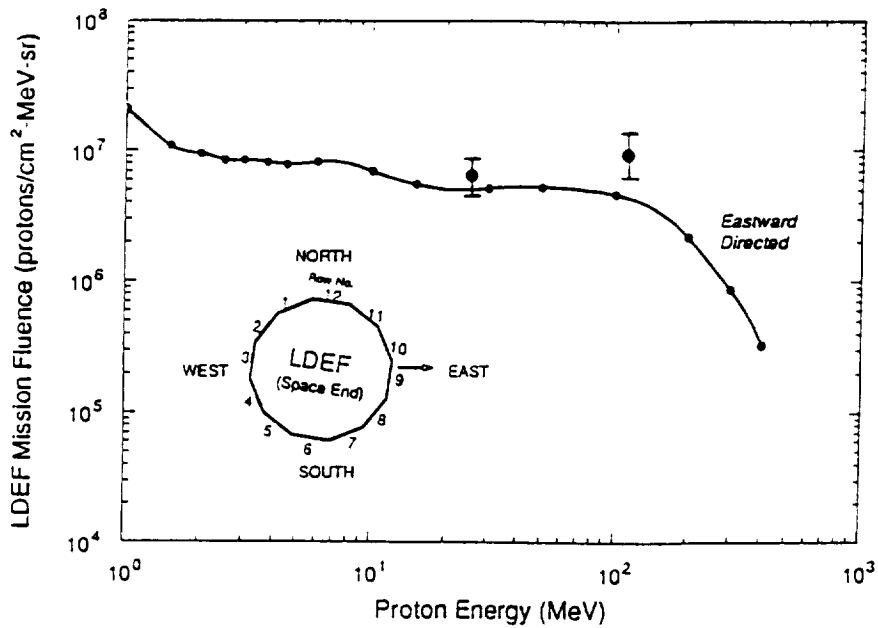


Figure 6: Comparison of calculated LDEF mission fluence of Eastward directed trapped protons (Armstrong and Colborn) with the upper limiting results of measurements.

at 0.6 and 9.5 g/cm² depths, respectively. However, not all of these tracks were due to primary protons. The contribution of secondary protons may be significant, especially at the higher shielding depths. On the other hand, not all primary protons reach their stopping points without nuclear interactions. We have estimated the survival probability of a proton to be 97% and 86% for the two shielding depths. Assuming that all tracks are from primary protons and taking into account the survival probability, we estimated an upper limit of the average mission fluence of trapped protons in the selected solid angle intervals. The corresponding energy intervals vary between 24 and 26 MeV for 0.6 g/cm² and between 109 and 118 MeV for 9.5 g/cm² shielding depths as the polar angle varies from 0° to 30°. The estimated average fluences are 6.3×10^6 and 9.2×10^6 tracks/(cm²·MeV) at the 25 and 114 MeV mean energies. The relative error due to counting statistics of these estimates is about 8%. Significantly larger error (about 25%) may be introduced from the estimation of the thickness of the sensitive layer. We suppose other sources of error are negligible compared to these estimates. The relative error of our experiment is estimated to be about 30%.

Figure 6 shows a comparison of our measurements with model calculations of Armstrong and Colborn[7]. This comparison shows a very good agreement at 25 MeV which may reflect that at the corresponding depth, the contribution of secondary particles is negligible. At 114 MeV, the experimental upper bound is significantly higher than that of the model calculations. This requires further analysis of contribution of secondary protons at this depth. Differences may also come from the fact that (probably) no absolutely identical solid angle intervals were used to measure and calculate fluences. These difficulties in the comparisons would disappear if calculation of directional distribution of stopping proton volume density were available. Concerning the observed high anisotropy of trapped protons, a measurement with better statistical power would also be reasonable for comparison of experimental results with model calculations.

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