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A METHOD FOR SIMULATING VAN ALLEN BELT PROTON ENERGY SPECTRA

By John W. Watts, Jr., and Martin O. Burrell
Space Sciences Laboratory

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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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John W. Watts, Jr. and Martin O. Burrell

NUCLEAR AND PLASMA PHYSICS DIVISION
SPACE SCIENCES LABORATORY

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John W. Watts, Jr. and Martin O. Burrell

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

ABSTRACT

To study radiation effects caused by geomagnetically trapped high energy protons, one must produce a proton source with the expected spectral characteristics. A method for generating such spectra using a spinning wheel of varying thickness is described. Resulting wheel shapes for two typical proton spectra are shown.

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INTRODUCTION

Film stacks will be carried to observe cosmic ray interactions on certain space flights passing through the magnetically trapped radiation belts around the earth. Although, in general, these flights will remain in the belts only short periods, some determination is needed of the expected film degradation caused by trapped protons. In making this determination, it is necessary to simulate the trapped proton energy spectrum by using a proton accelerator and irradiate the film to be used. It is extremely difficult, if not impossible, to vary the energy or number of protons rapidly in a controlled fashion for any of the accelerators now in use. The problem, then, is to establish a method that will allow rapid variation in the proton number and the energy of a proton accelerator beam; the goal is to simulate a given proton spectrum that can vary in number over an order of magnitude in the energy range between 10 MeV and 200 MeV.

THE METHOD

In the energy range of interest, two approximations (the straight-ahead approximation and the continuous slowing-down approximation) are valid for describing the transport of protons through material shields. Stated simply, these approximations mean that a proton will not be scattered from its initial direction by the shield and that the energy of the proton at any point in the shield is a continuous function of the initial energy and the distance traveled through the shield. Thus, if a slab of material is placed in a proton beam, the beam will come out of the other side, traveling in the same direction and containing the same number of particles, but the beam will have a reduced energy that will depend upon the initial beam energy, the thickness of the slab, and the type of material in the slab. By placing the film in such a beam described above and varying the slab thickness correctly with time, the effects of exposing the film to a given spectrum can be simulated. One process to quickly vary the slab thickness is to use a spinning wheel of varying material thickness as shown in Figure 1.

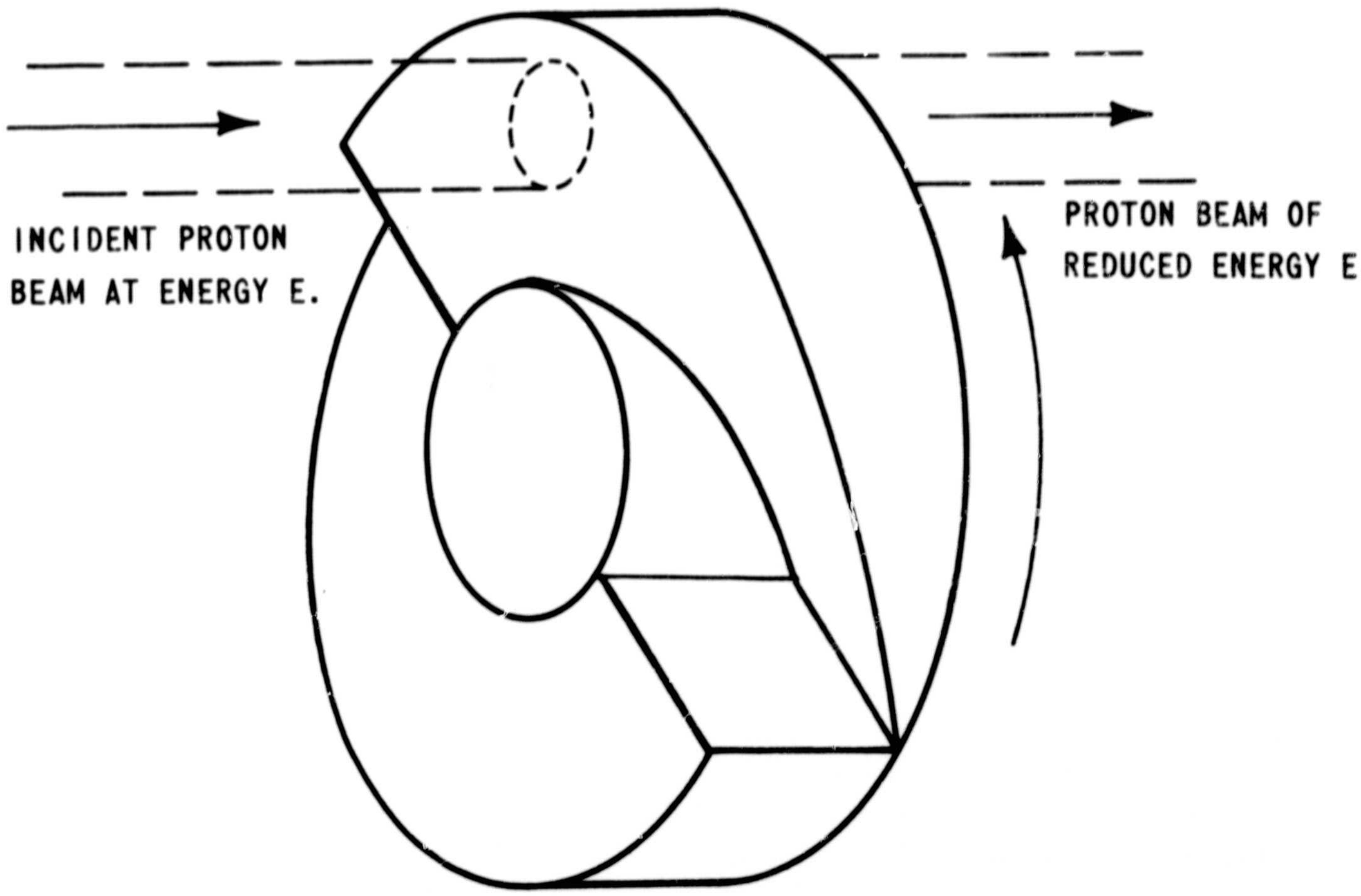

FIGURE 1. THE PROTON SPECTRUM WHEEL CONFIGURATION

ASSOCIATED PROBLEMS

The majority of the energy lost by a proton in passing through a slab is through interactions with the electrons in the slab. This is a statistical process; consequently, the protons coming out of the slab would be expected to have some distribution of energies instead of having a discrete energy. This corresponds to a distribution of path lengths about the mean path length. Reference 1 tabulates the root mean square straggling (the standard deviation of the distribution) for the mean path length required for a proton to lose all its energy. (This path length is the length of the actual path followed as opposed to the range, which is the straight line distance traversed in stopping.) For a 200 MeV proton stopped in aluminum, the deviation is 0.36613 g/cm^2 about a mean path length of 33.201 g/cm^2. For the range, which is 33.112 g/cm^2, the deviation should be about the same since the range is so close to the mean path length. The range of a 15-MeV proton is 0.34297 g/cm^2. Thus, if a slab of range thickness is placed in front of a 200 MeV proton beam, about half of the protons will be stopped, and most of those getting through the slab will have energies less than 15 MeV. This is the worst case possible. For thinner slabs the deviation of the energy distribution will be considerably less than 15 MeV. Since the trapped belt proton spectra to be reproduced do not have any sharp peaks, the smearing effects caused by the inability to produce discrete energies are not as important as they seem at first.

Perhaps the main problem in using a material slab to reduce a proton beam's energy is the possibility of nuclear interactions in the slab; this would result in the scattering of protons out of the beam, production of neutrons, and activation of the slab. The use of some light material such as aluminum will prevent activation of the slab.

The nuclear interactions can be divided into two classes, elastic and inelastic collisions. Elastic collisions leave the nucleus unexcited and produce no secondary particles, but the proton is scattered at some angle with its original direction. Generally, this scattering is very peaked in the forward direction except for materials of very low atomic number. In inelastic collisions for the energy range under consideration, the proton loses part or all of its energy to the nucleus, one or more secondary protons and neutrons may be produced, and again the proton is lost from the beam. R. G. Alsmiller of Oak Ridge National Laboratory, using a high-energy nucleon Monte Carlo transport code, calculated the expected neutron and proton spectra that would be produced by 160 MeV protons incident on an aluminum slab [2]. Some of the results of this calculation are shown in Table I. As can be seen, secondary protons can never account for more than about 3 percent of the total flux, and secondary neutrons make up about 20 percent of the total. The fractions given are for the total flux and not just the flux in the direction of the beam. A large fraction of these secondaries are expected to be scattered out of the beam direction or emitted isotropically in the case of evaporation neutrons.

In Table I the secondary neutrons are divided according to the process that produced them. The cascade neutrons, which account for about 5 percent of the total flux, are produced in direct interactions with the incident proton inside the nucleus. They are fairly energetic and have a forward-peaked angular distribution. Evaporation neutrons, which account for about 15 percent of the total flux, are produced by a process in which a proton excites the target nucleus, which, in turn, loses its excitation energy by the emission of a neutron or proton. These particles have fairly low energies ($<$20 MeV), and their angular distribution is isotropic. The angular distribution of evaporation neutrons causes that component of the flux to decrease very rapidly with increasing distance from the slab. (Most of the evaporation protons never get out of the slab.)

TABLE I. PRIMARY AND SECONDARY PROTON TRANSMISSION PER UNIT FLUX THROUGH VARIOUS ALUMINUM SHIELD THICKNESSES

Shield Thickness (g/cm^2)	Primary Protons	Secondary Protons	Cascade Secondary Neutrons	Evaporation Secondary Neutrons
5	0.9525	0.018	0.028	0.100
10	0.9025	0.030	0.048	0.126
15	0.8585	0.024	0.063	0.170
21	0.7975	0.001	0.068	0.180

The mean free path of a 20-MeV neutron between nonelastic collisions is 18 cm of aluminum. Thus, very few neutrons would be expected to have an interaction in a piece of photographic film. They might produce some activation in the surrounding equipment, but the fluxes are so small that this should not be a problem. If the total flux is not accounted for in the simulation, the secondary protons would be expected to slightly raise the high-energy side of the spectrum produced, since the low energy secondary protons are stopped in the slab. It was concluded that this was not a significant problem. By knowing the cross section for nuclear interactions for protons, it is fairly easy to determine the fraction of the primary protons scattered out of the beam and correct for this in calculating the thickness variation around the circumference of the wheel.

METHOD FOR CALCULATION OF THE WHEEL THICKNESS VARIATION

To determine the variation in the wheel thickness to produce a given spectrum given an incident beam of protons with energy E_0 and flux I_0, we proceed as follows. If the differential proton spectrum is described by $\phi(E)$, then

$$df = \frac{\phi(E)\,dE}{\int_0^{E_0} \phi(E)\,dE} \tag{1}$$

where df is the fraction of the total proton flux between 0 and E_0 that has energies between E and E + dE. If dS (E) is the fraction of the wheel circumference that is thick enough to reduce E_0 to energy E, then

$$\mathrm{df} = \frac{I_0\, e^{-\Sigma\, T(E_0,\, E)}\, d\, S(E)}{\int_0^1 I_0\, e^{-\Sigma\, T(E_0,\, E)}\, d\, S} \tag{2}$$

where $T(E_0, E)$ is the wheel thickness required to produce energy E from E_0; the exponential factor $e^{-\Sigma\, T(E_0,\, E)}$ is to correct for protons lost from the beam by nuclear interactions; Σ is the nuclear inelastic cross section; and the integral is just the total primary flux coming out of the slab. From equations (1) and (2),

$$\frac{\phi(E)\, dE}{\int_0^{E_0} \phi(E)\, d\, E} = \frac{I_0\, e^{-\Sigma\, T(E_0,\, E)}\, d\, S\, (E)}{\int_0^1 I_0\, e^{-\Sigma\, T(E_0,\, E)}\, d\, S} \tag{3}$$

or

$$d\, S\, (E) = \frac{\int_0^1 e^{-\Sigma\, T(E_0,\, E)}\, dS}{\int_0^{E_0} \phi(E)\, dE} \left[\phi(E)\, e^{\Sigma\, T(E_0,\, E)}\, dE\right] . \tag{4}$$

It is known that

$$\int_0^1 d\, S\, (E) = 1 ; \tag{5}$$

thus,

$$\frac{\int_0^1 e^{-\Sigma\, T(E_0,\, E)}\, d\, S \int_0^{E_0} \phi(E)\, e^{\Sigma\, T(E_0,\, E)}\, d\, E}{\int_0^{E_0} \phi(E)\, d\, E} = 1 \tag{6}$$

or

$$\int_0^1 e^{-\Sigma\, T(E_0,\, E)}\, d\, S = \frac{\int_0^{E_0} \phi(E)\, dE}{\int_0^{E_0} \phi(E)\, e^{\Sigma\, T(E_0,\, E)}\, d\, E} . \tag{7}$$

From equations (4) and (7), one gets

$$dS(E) = \frac{\phi(E)\, e^{\Sigma T(E_0,\, E)}\, dE}{\int_0^{E_0} \phi(E)\, e^{\Sigma T(E_0,\, E)}\, dE} \qquad (8)$$

cr

$$S(E') = \frac{\int_0^{E'} \phi(E)\, e^{\Sigma T(E_0,\, E)}\, dE}{\int_0^{E_0} \phi(E)\, e^{\Sigma T(E_0,\, E)}\, dE} \quad . \qquad (9)$$

To obtain $T(E_0, E)$, one uses the relationship

$$R(E_0) = R(E) + T(E_0, E) \qquad (10)$$

or

$$T(E_0, E) = R(E_0) - R(E) , \qquad (11)$$

where R(E) is the mean range of a proton at energy E.

To minimize problems caused by secondaries and activation, aluminum was selected as the material for the wheel, and a 160-MeV beam energy was used. The proton range was approximated by

$$R(E) = \frac{a}{2b} \ln (1 + 2b E^r) \qquad (12)$$

from Reference 3. For aluminum, values for the parameters a, b, and r are as follows: $a = 2.794 \times 10^{-3}$, $b = 2.346 \times 10^{-6}$, and $r = 1.775$ from Reference 4, where E in in millions of electron volts and R(E) is in grams per square centimeter. (The fit is good to better than 3 percent over the range of interest.) The aluminum density assumed was 2.692 g/cm^3.

Since the inelastic cross section is a function of energy and since the energy of the proton changes as it passes through the slab, the apparent inelastic cross section to account for the primary protons lost in a slab is a function of the initial proton energy and the slab thickness. To obtain the effective inelastic cross section, Alsmiller's Monte Carlo results [2] for primary flux transmission were taken from Table 1, the effective cross section was determined, and these values were combined with the known cross section for 160-MeV protons and fitted with the equation.

$$\Sigma = 4.01 \times 10^{-4}\ T + 8.92 \times 10^{-3},$$

where T is the thickness in centimeters, and Σ is the effective inelastic cross section in square centimeters per gram. Elastic scattering was assumed to be so peaked in the forward direction that in these calculations it could be ignored.

RESULTS

Figure 2 shows the wheel thickness, T, in centimeters versus the fraction of the total circumference, S, having thickness greater than T. The spectrum to be simulated, shown in Figure 3, was obtained using data described in Reference 5 and a computer program described in Reference 6.

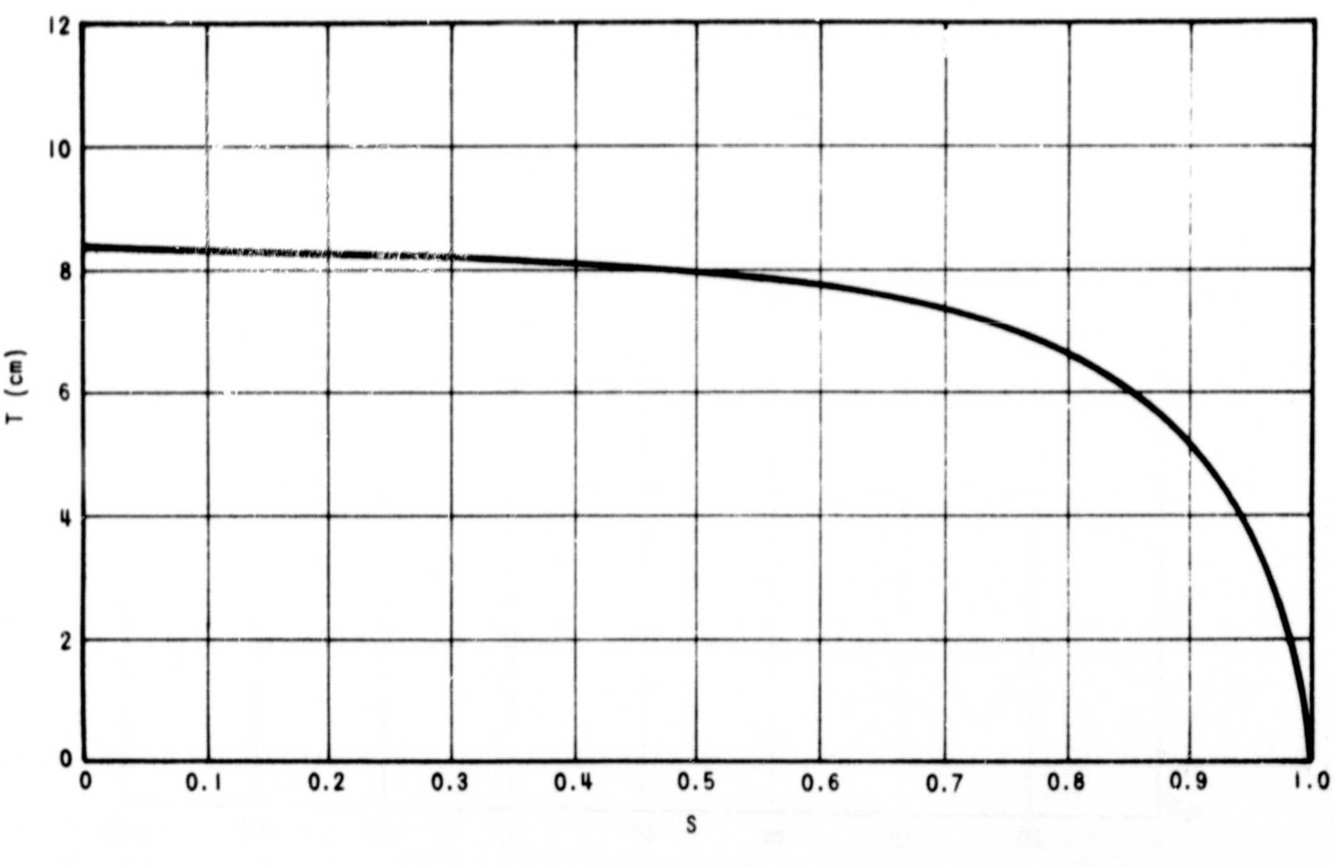

FIGURE 2. WHEEL SHAPE FOR THE SPECTRUM OF PROTONS IN A 389 km (210 n. mi.), 50 DEGREE CIRCULAR ORBIT

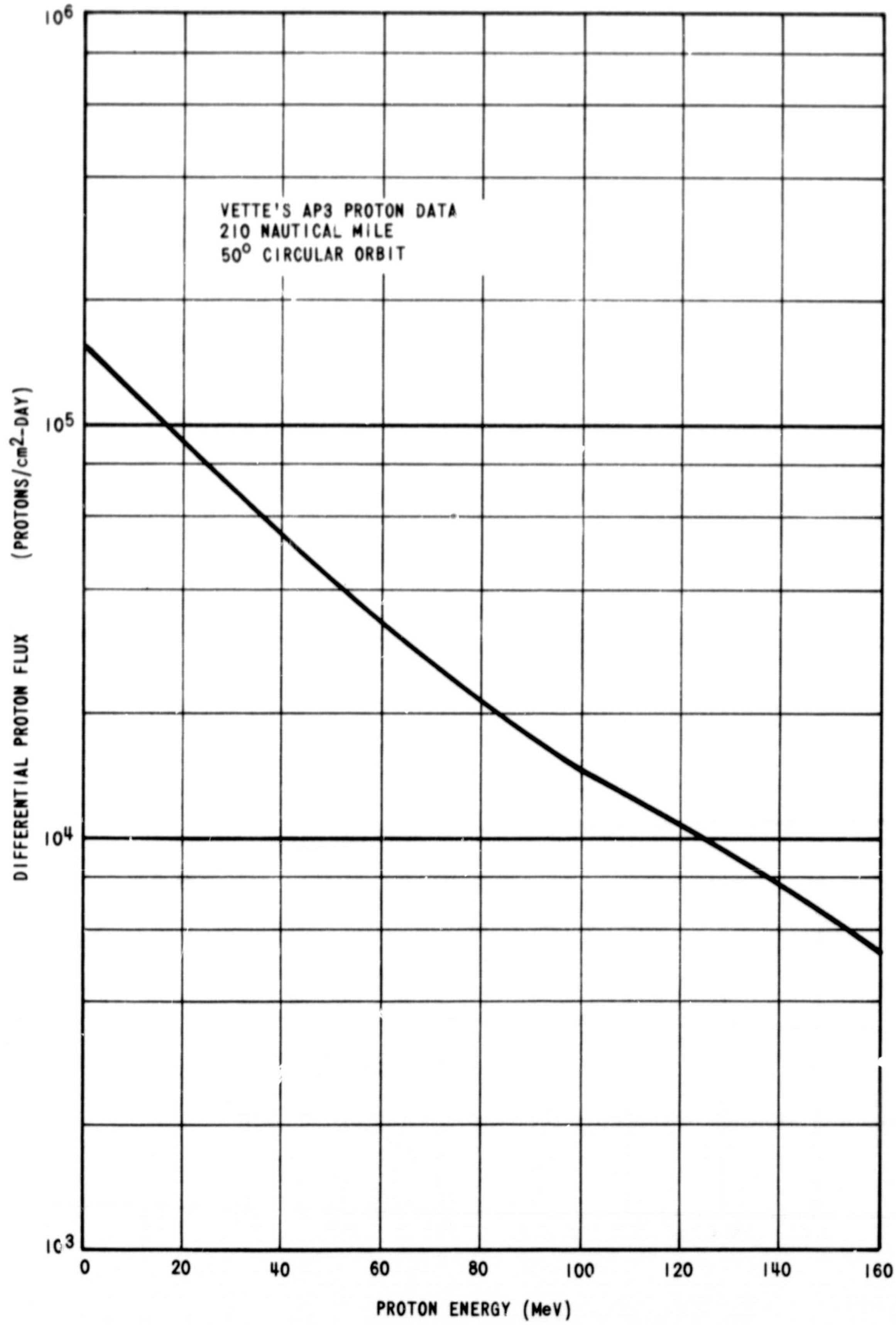

FIGURE 3. MAGNETICALLY TRAPPED PROTON SPECTRUM FOR A 389 km (210 n. mi.), 50 DEGREE CIRCULAR ORBIT

The actual wheel used in the experiment was slightly more complicated than the one shown in Figure 2. The incident beam had an energy of 160 MeV, but there were plastic scintillators 1.296 g/cm^2 thick located in front of and behind the wheel to monitor the proton beam. Thus, the highest energy passing through the whole apparatus was 145.9 MeV. The proton spectrum to be simulated was known to 600 MeV. To account for particles with energies greater than 145.9 and less than 600 MeV, two gaps were left in the wheel. Their total width was proportional to the fraction of the total flux with energies between 145.9 MeV and 600 MeV. The resulting wheel shape is shown in Figure 4. The spectrum to be simulated is shown in Figure 5.

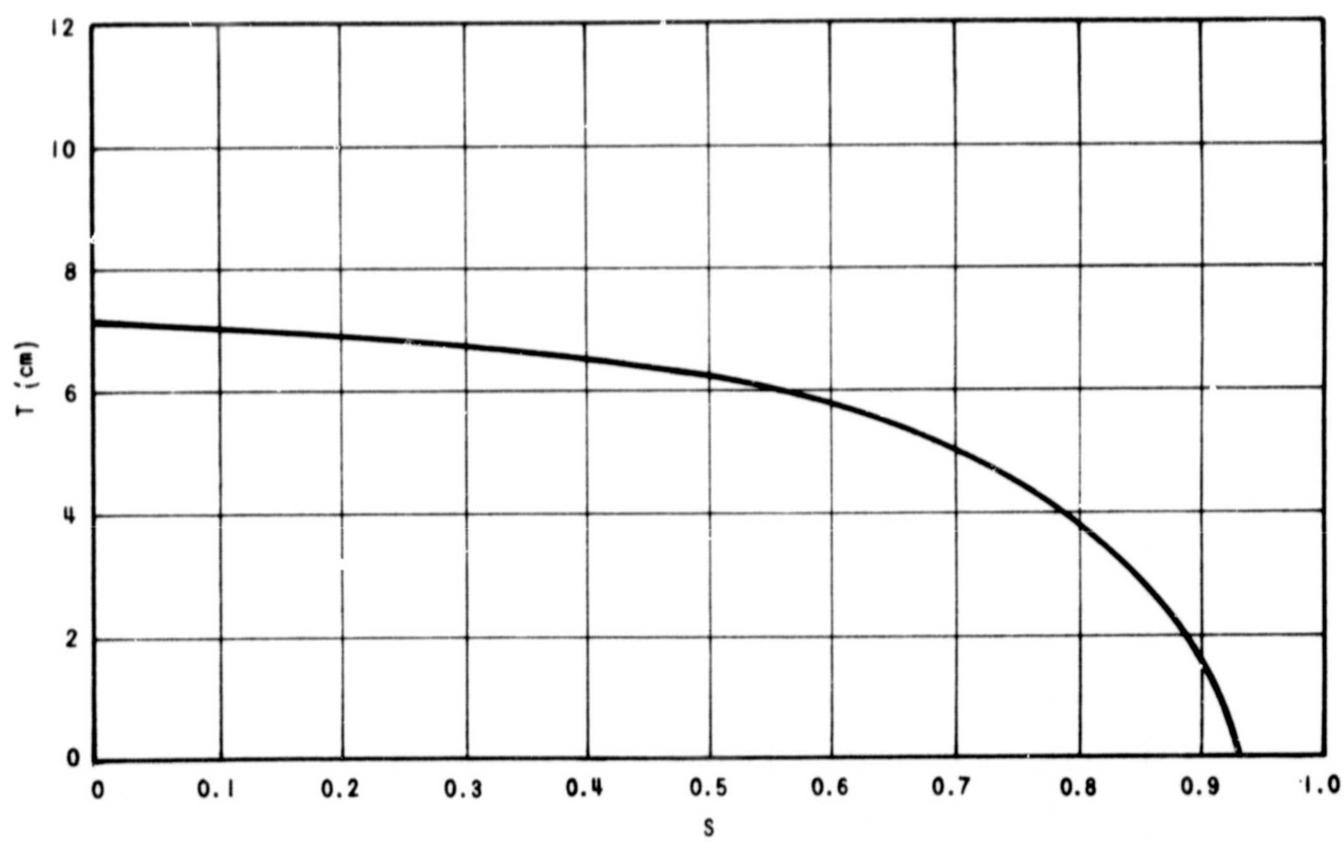

FIGURE 4. WHEEL SHAPE FOR THE SPACTRUM SHOWN IN FIGURE 5 FOR AN INCIDENT BEAM OF ENERGY OF 160 MeV, WHERE PLASTIC SCINTILLATORS 1.296 g/cm^2 ARE PLACED BEFORE AND AFTER THE WHEEL

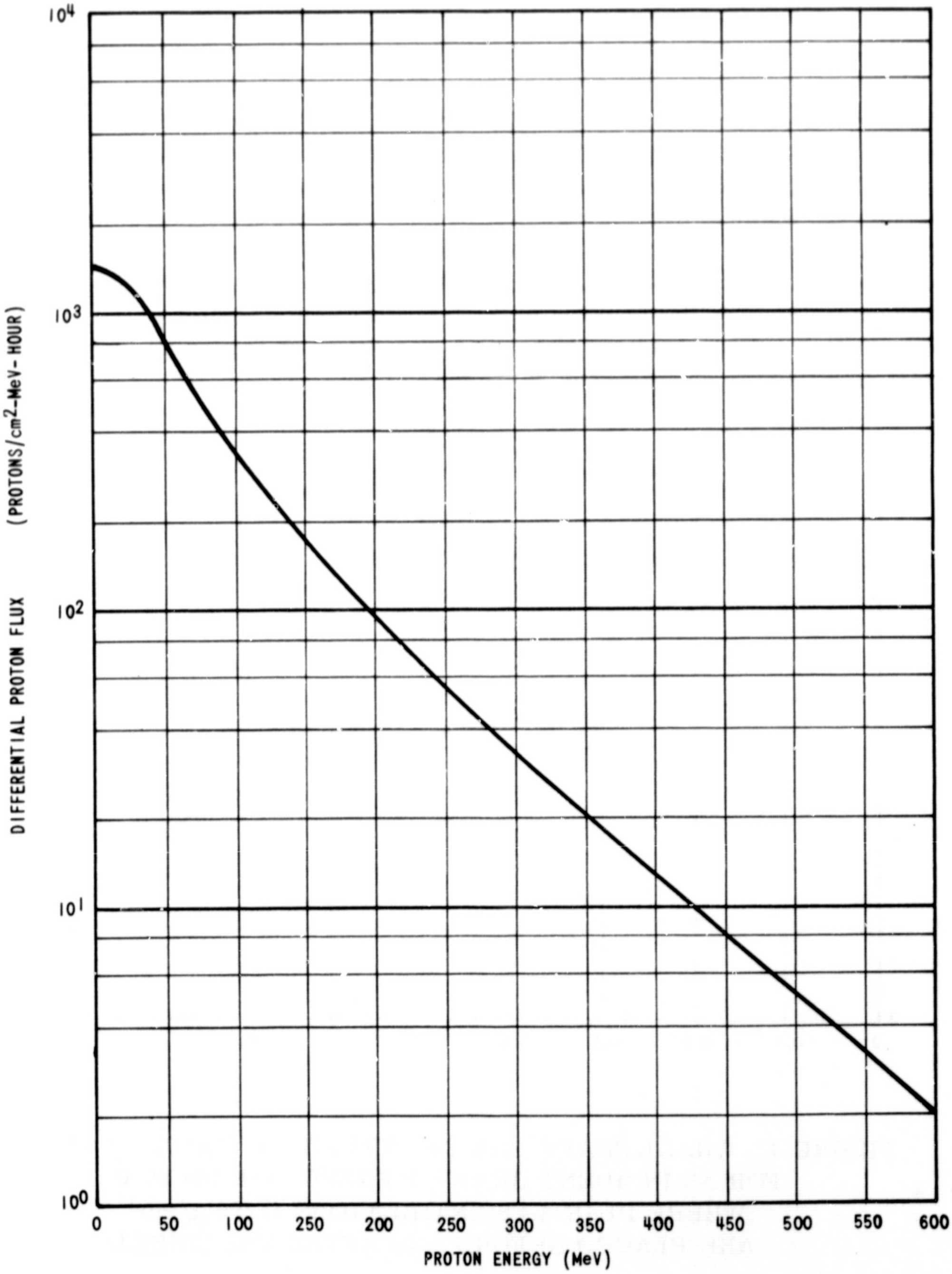

FIGURE 5. MAGNETICALLY TRAPPED PROTON SPECTRUM FOR THE ATM ORBIT

Lester Katz did the actual mechanical design work on the machining of the wheel shape and the development of a drive mechanism to spin the wheel. Figure 6 shows a photograph of the final operational device used in the experiment.

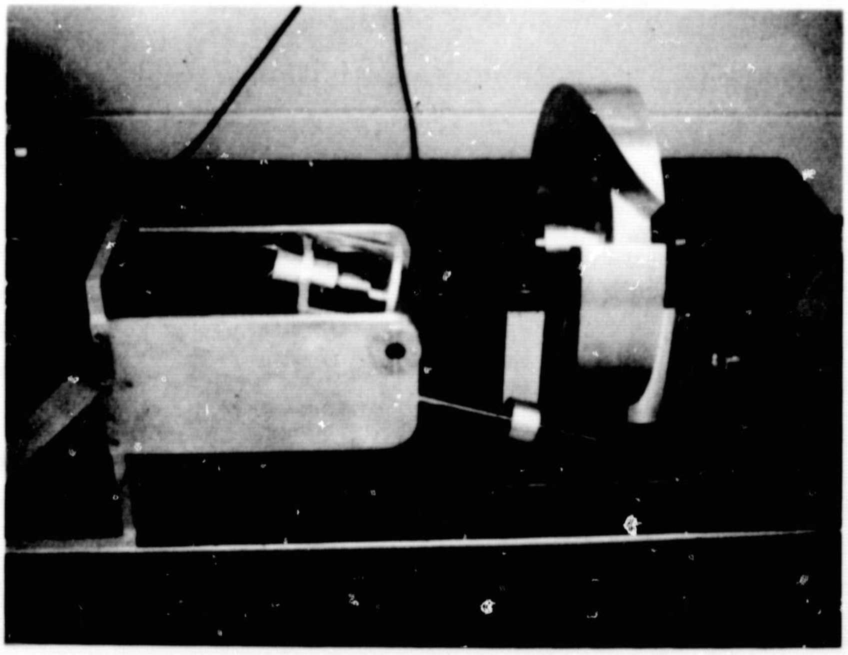

FIGURE 6. THE WORKING APPARATUS USED IN THE EXPERIMENT

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