NASA TECHNICAL NOTE

NASA TN D-6194

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NASA TN D-6194

A FOCUSED ČERENKOV RADIATION DETECTOR FOR PROTON BEAM ENERGY MEASUREMENTS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1971

1. Report No. NASA TN D-6194	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A FOCUSED CERENKOV RADIATION DETECTOR FOR PROTON BEAM ENERGY MEASUREMENTS		5. Report Date April 1971
		6. Performing Organization Code
7. Author(s) Sherwin M. Beck and Clemans A. Powell, Jr.		8. Performing Organization Report No. L-7501
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		10. Work Unit No. 124-09-21-01
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A focused Cerenkov radiation detection system has been developed and was used to measure the beam energy and energy spread of the nominal 600-MeV proton beam at the NASA Space Radiation Effects Laboratory (SREL). The inherent resolution of the detection system was 4.2 percent full width at half maximum for the measured proton beam energy of 557.6 ± 2.5 MeV. The energy spread of the proton beam was calculated to be 14 MeV full width at half maximum.

17. Key Words (Suggested by Author(s)) Čerenkov detector Energy measurement	18. Distribution Statement Unclassified – Unlimited

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 9	22. Price* $3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

A FOCUSED ČERENKOV RADIATION DETECTOR FOR PROTON BEAM ENERGY MEASUREMENTS

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SUMMARY

A focused Čerenkov radiation detection system has been developed and was used to measure the proton beam energy and energy spread of the synchrocyclotron at the NASA Space Radiation Effects Laboratory (SREL). The angle of emission of the visible Čerenkov radiation was determined for a fused-quartz-plate Čerenkov radiator. The inherent energy resolution of the detection system was 4.2 percent full width at half maximum for the measured proton beam energy of 557.6 ± 2.5 MeV. The energy spread of the proton beam was calculated to be 14 MeV full width at half maximum. The use of such a detection system is not limited to protons of nominally 600-MeV energy but could, with slight modification, provide energy information for a variety of charged particles and particle energies.

INTRODUCTION

Measuring the scattering and interactions of a beam of charged particles with materials requires a knowledge of the beam energy, flux and direction. By means of relatively simple ionization chambers and counters, the intensity and direction of the beam can be monitored easily during an experiment without interfering with the experimental measurements. The beam energy, however, is difficult to measure for two reasons: The measuring apparatus usually interferes with other experimental measurements, and the long time required for data analysis prevents frequent monitoring of the energy.

The usual methods of determining the beam energy from an accelerator are to stop the particles in a scintillation detector, to use magnetic fields to deflect the particles and allow momentum analysis, and to degrade the energy sufficiently with known absorbers to obtain range-energy information. The use of a scintillation detector for energy measurements requires, first of all, that some known monoenergetic source of the particle type exists near the energy to be determined so that the detector can be calibrated. This approach is feasible only for low-energy (less than 10 MeV) electrons and alpha particles. The use of magnetic deflection involves very large, expensive, and well-calibrated magnets to furnish good energy resolution. Although the range-energy method involves relatively simple and inexpensive apparatus, the analysis of data is rather tedious and time consuming and would be relatively inconvenient for frequent checks on the beam energy during the course of a scattering experiment.

The purpose of this report is to describe a detection system which was developed for measuring the energy and energy spread of the 600-MeV proton beam from the synchrocyclotron at the NASA Space Radiation Effects Laboratory (SREL). The system uses a focused Cerenkov radiation detector based on a design reported in reference 1. Čerenkov radiation is emitted when a charged particle passes through a medium with a velocity greater than the velocity of light in the medium. (See ref. 2.) The detection system described in reference 1 provided only relative energy measurements; whereas, the system reported herein has been used for absolute measurements.

SYMBOLS

c	velocity of light in vacuo, m/sec
N	number of photons
n	number of photoelectrons emitted from photocathode of photomultiplier tube per incident photon
R	response of Čerenkov radiation detection system per unit wavelength
T	transmission of focusing lens
v	velocity of a proton, m/sec
Y	relative spectral response of photomultiplier tube
$\beta = v/c$	
λ	wavelength of light from Čerenkov radiator, nm
η	index of refraction
θ	Čerenkov angle, deg

The energy unit MeV is equal to 1.6021×10^{-13} joule.

EXPERIMENTAL SETUP AND TESTS

The basic setup for the Čerenkov radiation detection system is shown in figure 1. A 1.27-cm-thick and 7.62-cm-diameter fused-quartz plate was used as the Čerenkov radiator. Photons emitted at an angle from the beam direction were reflected by a vapor-deposited aluminum coating on the back surface of the quartz plate to a 6.35-cm-diameter lens with a 15.0-cm focal length. Parallel light from the quartz plate was thus focused on an aperture of 0.15-cm diameter and on the photocathode of a photomultiplier tube. The gain of the photomultiplier tube was 1×10^8 at 1800 volts. Electrical pulses from the photomultiplier tube were amplified, rectified, integrated, and fed to a digital voltmeter. The analog output from the digital voltmeter was then recorded on a chart recorder.

The entire Čerenkov detector assembly, including the quartz plate, lens, and photomultiplier tube, was housed in a light-tight enclosure, which could pivot about the center of the quartz plate. The assembly was driven by a reversible synchronous motor at approximately 0.1 degree per second on a horizontal table. A high-precision linear

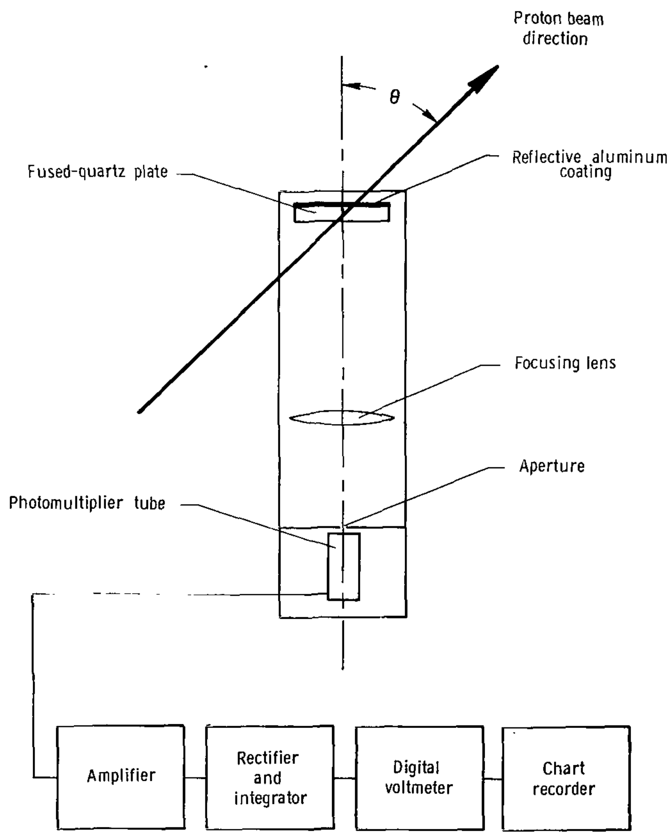

Figure 1.- Čerenkov radiation detection system.

otentiometer was coupled to the motor shaft and served as one leg of a Wheatstone ridge. A similar potentiometer, which served as the balancing leg of the bridge, was ocated in the remote readout area along with the motor controls. The angle of the erenkov assembly with respect to a reference line on the supporting table was meaured within $\pm 0.05^{\circ}$ by balancing the bridge.

The path of the proton beam was determined by placing photographic film at sevral locations along the supposed beam path. After exposure, the center of the beam was ocated on each film, and 1-mW laser was set up along the center of the proton beam path. he reference line on the table was thus alined with the beam path within $\pm 0.05^{\circ}$.

The photographic films also furnished information about the divergence of the proton eam. Figure 2 shows the beam transport system for approximately the last 25 meters efore the Čerenkov detector location. Only the magnets and features of the transport ystem used in the present investigation are shown. Reference 3 gives a complete diaram of the SREL proton facility and some of the available beam characteristics. A .27-cm-diameter collimator was placed before the bending magnet labeled M 6, and a ..91-cm-square collimator was placed between M 6 and M 7. The only focusing quadruole magnets used after M 6 were Q 21 and Q 22. These quadrupoles were approximately

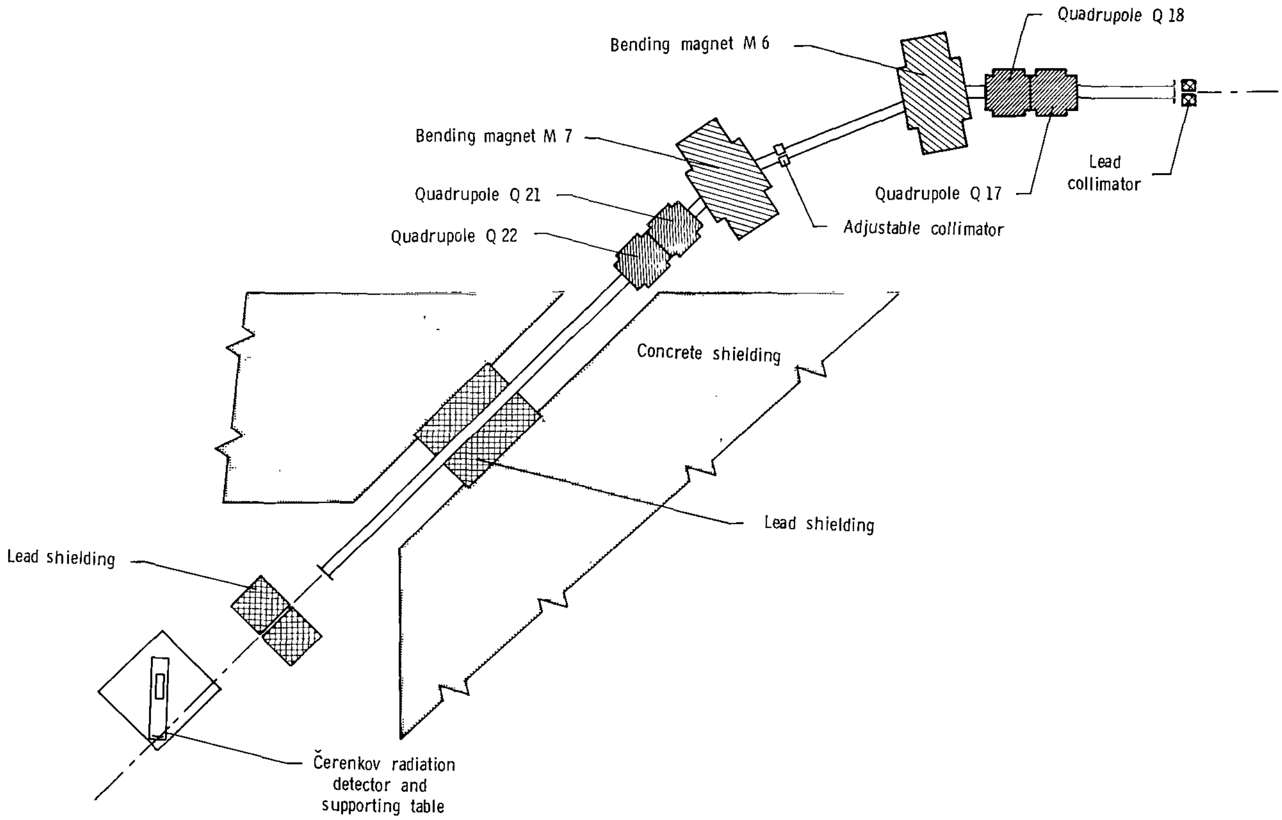

Figure 2.- Proton beam transport system.

15 meters upstream from the Čerenkov detector assembly. The aperture in the lead shielding between the beam transport system and the Čerenkov detector was 5.08 cm square and did not intercept the proton beam. All but one of the photographic films were placed in the beam path between the end of the beam transport system and the Čerenkov detector; the one remaining film was placed approximately 3 meters after the Čerenkov detector. The proton beam diameter was 2.2 cm, and the horizontal and vertical divergences of the beam were determined to be less than 0.1° and 0.3°, respectively. The vertical divergence is of little consequence because the Čerenkov angle measurements were made in the horizontal plane at approximately 30°.

A typical experimental measurement of the beam energy and energy spread consisted of setting the Čerenkov detector assembly at 26.0°, starting the drive motor and chart recorder simultaneously, then stopping the chart recorder when the assembly passed through 33.0°. Measurements were also made in the opposite direction to determine errors in response time of the electrical circuitry. None of the measurements gave deviations from the mean of the peak output greater than 0.09°.

RESPONSE OF THE ČERENKOV DETECTOR

Before the data from the Čerenkov detector can be used to determine the energy spread of the proton beam, the response of the system to monoenergetic protons must be determined. The direction of the light output of a Čerenkov radiator exposed to a beam of particulate radiation of velocity v is wavelength dependent. The angle of emission of the light photons (as measured from the velocity vector of the particulate radiation) is given by the Čerenkov relationship (ref. 2),

$$\cos\theta = \frac{1}{\beta\eta} \tag{1}$$

where $\beta = v/c$, v is the velocity of the particles, c is the velocity of the light in vacuo, and η is the index of refraction of the radiating medium.

It has been shown in reference 2 that the number of photons per unit wavelength $\frac{dN(\lambda)}{d\lambda}$ emitted from a Čerenkov radiator depends on the wavelength by the relationship

$$\frac{dN(\lambda)}{d\lambda} \propto \frac{1}{\lambda^2} \tag{2}$$

where $N(\lambda)$ is the number of photons emitted over some path length, and λ is the photon wavelength. Since the photons are emitted with a continuous distribution of wavelengths, the angle of emission is not a unique function of the velocity of the particulate radiation causing the emission. The output of the photomultiplier tube and the transmission of all optical materials between the Čerenkov radiator and photomultiplier tube are also wavelength dependent. The number of photoelectrons $n(\lambda)$ emitted from the photocathode of a photomultiplier tube per incident photon is

$$n(\lambda) \propto \frac{Y(\lambda)}{\lambda} \tag{3}$$

where $Y(\lambda)$ is the relative spectral response of the photocathode as modified by the transmission of the glass envelope of the tube. The variation (with wavelength) of the relative spectral response of the tube used in this apparatus is shown in figure 3; this information was obtained from the manufacturer's literature.

When the response of the photomultiplier tube, the transmission of the focusing lens, and the output of the Čerenkov radiator are taken into account, the response of the detector assembly $R(\lambda)$ is

$$R(\lambda) \propto \frac{Y(\lambda)T(\lambda)}{\lambda^3} \tag{4}$$

where $T(\lambda)$ is the transmission of the focusing lens. The relative response is shown in figure 4. As can be seen, the response was peaked at a wavelength of 380 nm; therefore, the index of refraction for this wavelength was used in the Čerenkov relationship (eq. (1)) to determine the proton beam energy.

Figure 5 shows a typical record from the Čerenkov detector as a function of the angle θ. The mean value of the peak output from all such measurements has been determined to be at 29.35° with a standard deviation of 0.05°. By using this value of θ in equation (1), the relative velocity β was determined to be 0.7789, which gives a mean proton beam energy of 557.6 MeV.

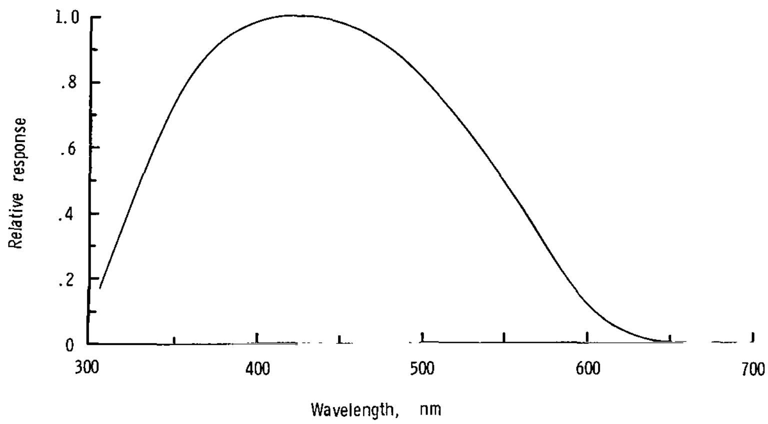

Figure 3.- Relative spectral response of photomultiplier tube.

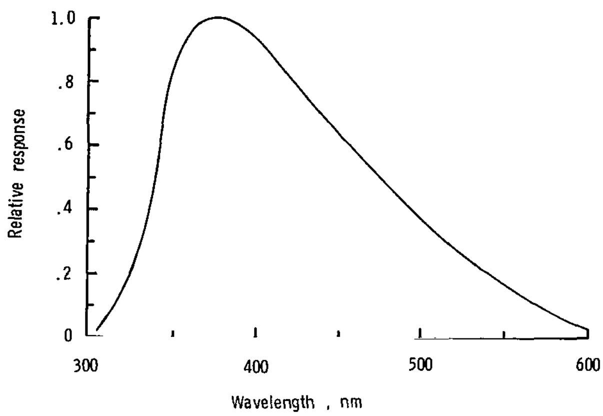

Figure 4.- Relative response of Čerenkov radiation detection system to 557.6-MeV protons as a function of wavelength of emitted light.

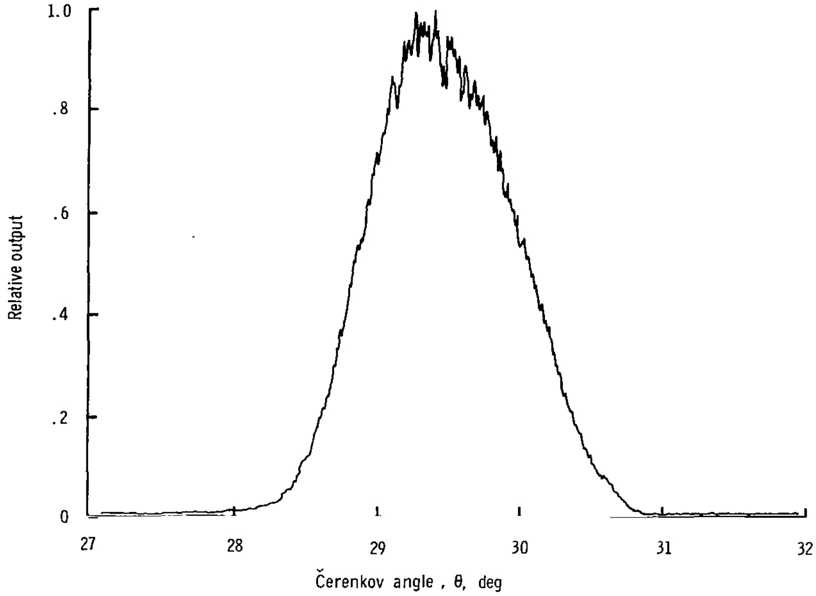

Figure 5.- Relative output of Čerenkov radiation detection system as a function of Čerenkov angle.

From the data presented in figure 4, and with $\beta = 0.7789$ and the appropriate indices of refraction, the response of the Čerenkov detector was found as a function of angle for protons with an energy of 557.6 MeV. Figure 6 shows the results of these calculations. The full width at half maximum for the peak is 1.05°. Analysis of the measurements by use of the Čerenkov detector in the SREL proton beam gave a full width at half maximum of 1.29° with a standard deviation of 0.02°, which corresponds to 24.50 MeV full width at half maximum and a standard deviation of 0.38 MeV for 557.6-MeV protons. Removal of the instrument response resolution gives a beam resolution of 0.74° or 14 MeV

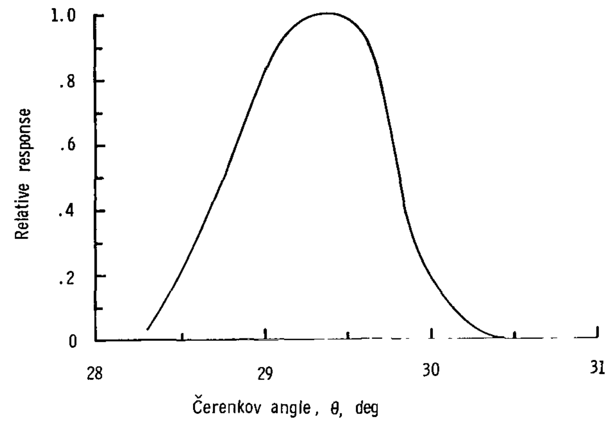

Figure 6.- Relative response of Čerenkov radiation detection system to 557.6-MeV protons as a function of Čerenkov angle.

full width at half maximum. All measurements indicated that the distributions were asymmetrical and spread toward higher energies as shown in figure 7 (which was made by smoothing the data of figure 5 and changing the abscissa from degrees to energy). If measurement uncertainties are considered, including the angle between the Čerenkov detector assembly and the reference line, alinement of the reference line with the beam direction, and statistical variations in the measurements, the energy measurements of 557.6 MeV should be accurate within $\pm 0.10^{\circ}$ or ± 2.5 MeV.

The use of a focused Čerenkov detector such as described in this report is not limited to protons of nominally 600-MeV energy. This particular design can be used over the proton energy range from approximately 400 MeV to 2000 MeV. By proper selection of the Čerenkov radiator material and thickness, the same detector configuration can be used for the following particle types and approximate energy ranges: protons, 150 MeV to 4000 MeV; pi-mesons and mu-mesons, 20 MeV to 300 MeV; and alpha particles, 700 MeV to 10 000 MeV.

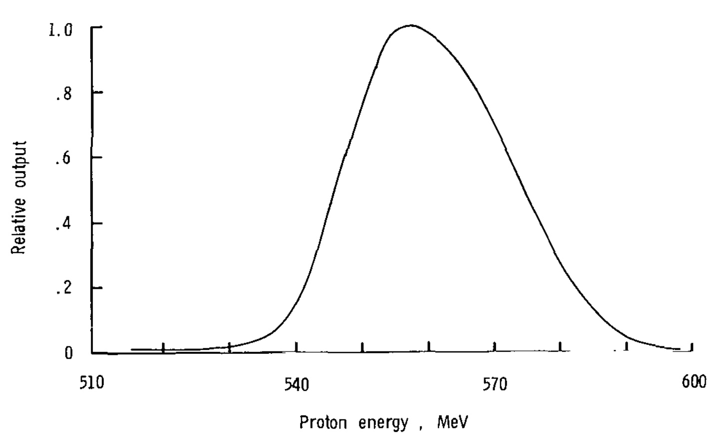

Figure 7.- Typical smoothed output of Čerenkov radiation detection system as a function of proton energy.

In principle this technique could also be used for electron velocity determination. However, the electrons, because of their small mass, can undergo large-angle scattering which would severely degrade the system resolution.

CONCLUSIONS

A focused Čerenkov radiation detection system has been constructed and was used to determine the energy and energy spread of the primary proton beam of the synchrocyclotron at the NASA Space Radiation Effects Laboratory. The following conclusions were noted:

1. The mean value of the proton beam energy was 557.6 MeV ± 2.5 MeV for the beam transport system adjusted for an essentially parallel beam of 2.2-cm diameter.

2. The resolution of the Čerenkov radiation detection system was 4.2 percent or 24.50 MeV full width at half maximum at 557.6 MeV.

3. The energy spread of the proton beam was 14 MeV full width at half maximum.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., February 18, 1971.

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