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X-Ray transition radiation from high energy particles

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Abstract. X-ray transition radiation is used to measure the Lorentz factor of relativistic particles. At energies approaching $\gamma = E/mc^2 \sim 10^5$, transition radiation detectors can be optimized by using thick (~125-250 μm) radiator foils with large (~5-10 mm) spacings. Such a configuration implies the production of x-rays of energy ≥ 100 keV and the use of scintillators as the x-ray detectors. Compton scattering of the x-rays out of the particle beam then becomes an important effect. We discuss the design of such high energy transition radiation detectors, present the results of detailed simulations, and apply the results to the ACCESS cosmic ray experiment proposed for the Space Station.

1 Introduction

Transition radiation (TR) is produced when a charged particle crosses the interface between two materials with different dielectric constants, resulting in the rapid rearrangement of the particle's electric field as it passes from one material to the next. Detailed calculations of the TR phenomenon are given in the literature (e.g. Ter-Mikaelian, 1972; Cherry, 1978); only the relevant properties are summarized here. For highly relativistic particles ($\gamma = E/mc^2 \gg 1$) the radiation is emitted at x-ray frequencies. The spectrum produced depends on the plasma frequencies and thicknesses of the two materials and the energy of the particle. Typically, the materials used are a low atomic number solid such as plastic, with plasma frequency ω_1, and a gas or vacuum with plasma frequency ω_2. Radiation is emitted up to a frequency $\gamma\omega_1$, beyond which the spectrum cuts off. The total intensity produced from a single interface is proportional to $Z^2\gamma$, where Z is the charge of the particle.

The intensity of the TR from a single interface is quite weak. Therefore, in practical applications, a 'radiator' is constructed with a large number N of thin foils of thickness l_1 separated by a distance l_2, with transition radiation produced at the $2N$ interfaces. Interference effects from the superposition of the amplitudes of the emitted radiation at each interface give rise to pronounced minima and maxima in the spectrum, with most of the energy emitted at the highest frequency maximum near

$$\omega_{\max} = \frac{l_1 \omega_1^2}{2\pi c}. \tag{1}$$

As the particle energy increases, the total energy radiated increases up to a Lorentz factor

$$\gamma_s = \frac{0.6\omega_1}{c}\sqrt{l_1 l_2} \tag{2}$$

above which saturation sets in due to the interference. The typical frequency $\omega_{\max}$ and saturation energy γ_s can be tuned by varying the radiator foil material, thickness, and separation.

An x-ray detector appropriate for absorbing the TR x-rays must be placed after the radiator. The radiation is emitted at an angle $\theta \sim 1/\gamma$ with respect to the incident particle direction, so the x-rays typically cannot be separated spatially from the ionization energy deposited in the detector by the particle itself. Therefore the detector must be made thin in order to minimize the ionization signal, yet with sufficient stopping power to absorb the x-rays. For $\omega_{\max}$ less than about 40 keV, gaseous detectors are typically employed. In order to improve statistics and for redundancy, a complete transition radiation detector (TRD) is comprised of multiple layers of radiators and x-ray detectors. Such TRDs have been used successfully both at accelerators (e.g. Cherry et al., 1974; Swordy et al., 1982; Detoeuf et al., 1989) and in space, where cosmic ray nuclei have been detected with $\gamma \geq 3 \times 10^3$ with the Space Shuttle CRN experiment (Grunsfeld et al., 1988; Swordy et al., 1990).

The Advanced Cosmic ray Composition Experiment on the Space Station (ACCESS) mission (Wefel and Wilson, 1999; Israel et al., 2000) has been baselined to include a

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TRD capable of measuring the energies of cosmic rays up to γ~10^5 for $Z > 3$. The current TRD designs must then be optimized for high energies. Here we discuss the design of such a high energy TRD including radiator material and dimensions as well as choice of x-ray detectors. Results of an accelerator test of a high energy TRD prototype are presented, as well as calculations and detailed simulations of high energy TRD configurations. These are then applied to the design of the ACCESS TRD.

2 High energy TRD design and accelerator results

As can be seen from Eq. 2, in order to increase the saturation energy of the TRD, one must increase some combination of the foil plasma frequency ω_1, the foil thickness l_1, and/or the spacing l_2. Restrictions on the height of a space instrument constrain l_2. Thus, in order to obtain a saturation energy as high as γ_s~10^5, thick dense foils must be used, for example Teflon (ρ = 2.2 g/cm^3, ω_1 = 29.6 eV) foils 250 µm thick with spacing 5 mm.

Increasing the foil density and thickness also increases ω_{max} (Eq. 1). For reasonable spacings (e.g. a few mm), γ_s~10^5 implies $\omega_{max} > 100$ keV. The gaseous detectors used in typical low energy TRDs are transparent to x-rays of these energies. Inorganic scintillators such as NaI or CsI are more effective hard x-ray detectors, but the large ionization energy deposit may potentially overwhelm the TR x-ray signal. Fortunately, for x-rays above ~30 keV, Compton scattering in the low atomic number foil material becomes important, so that a significant number of the TR photons scatter away from the path of the particle. This allows the TR signal to be spatially separated from the ionization signal. Thus, a segmented detector, or detectors located out of the path of the particle, can be used to detect the TR x-rays uncontaminated by the ionization energy.

In order to test this, a TRD was designed and built with six identical radiators of 50 foils, with each radiator surrounded by detectors on three sides parallel to the beam. Each individual detector consisted of a 5 mm thick NaI scintillator viewed by a 130 mm photomultiplier tube (Fig. 1). These out-of-the-beam scintillators only detected the TR x-rays Compton scattered at large angles away from the incident particle beam. The instrument was exposed in the CERN SPS H2A test beam line to secondary electron beams with energies from 7 to 150 GeV. Various radiator foil thicknesses and materials were tested, including polyethylene (ω_1= 20.9 eV), Mylar (ω_1= 24.5 eV), and Teflon. Fig. 2 shows the average number of photons measured per detector per event for three radiator configurations. As can be seen, an appreciable number of TR photons are indeed Compton scattered out of the beam and detected. The data demonstrate that saturation energies of γ_s~10^5 are clearly attainable.

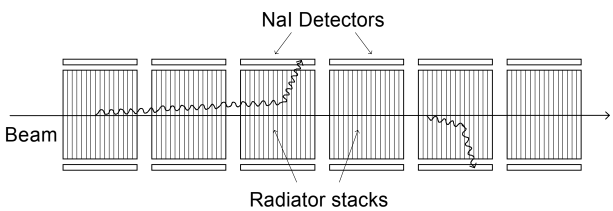

Fig. 1. Experimental setup, as seen from above, for electron beam tests of radiator configurations and TR Compton scattering. An additional NaI detector (not shown) was positioned above each radiator.

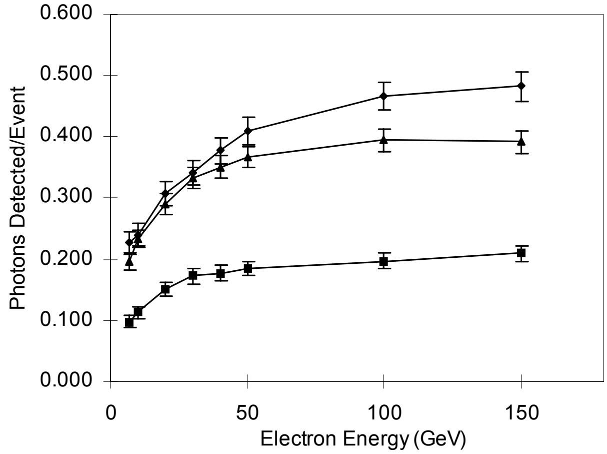

Fig. 2. Accelerator data showing the average number of photons detected per detector per event at various electron energies for two different radiator materials and foil thicknesses: 250 µm Teflon (*diamonds*), 250 µm Mylar (*triangles*) and 125 µm Mylar (*squares*). All three configurations had a spacing of 3.2 mm. The error bars represent statistical errors. Results are shown after subtracting the background measured with a solid Teflon or Mylar target of the same total thickness as the foil radiator.

3 TRD simulations and application to ACCESS

A key science goal for the ACCESS Space Station cosmic ray experiment is the measurement of the spectra of cosmic ray nuclei at energies approaching 10^{14} eV/nucleon ($\gamma = 10^5$), corresponding to total energies $> 10^{15}$ eV for nuclei with $Z \geq 6$. Whereas previous experiments, for example CRN, have attained saturation energies near $\gamma_s \sim 2 \times 10^4$, Fig. 2 shows an increasing TR yield with Lorentz factor up to $\gamma_s \sim 10^5$. A schematic of a possible detector design suitable for a high energy Space Station experiment is shown in Fig. 3. It has been known for some time that the TR yield from an irregular material (e.g., a foam or "bubble" structure) is essentially the same as that from a regular periodic radiator as long as the average foam or bubble wall thickness is equal to l_1 and the cell size is equal to l_2 and as long as the deviations of the actual cell dimensions are sufficiently small (Garibian et al., 1974; Prince et al., 1975). Teflon straws with outer diameter ~5 mm and wall thickness ~250 µm or standard aluminum honeycomb with average cell diameter $l_2 \sim 4$ mm and foil

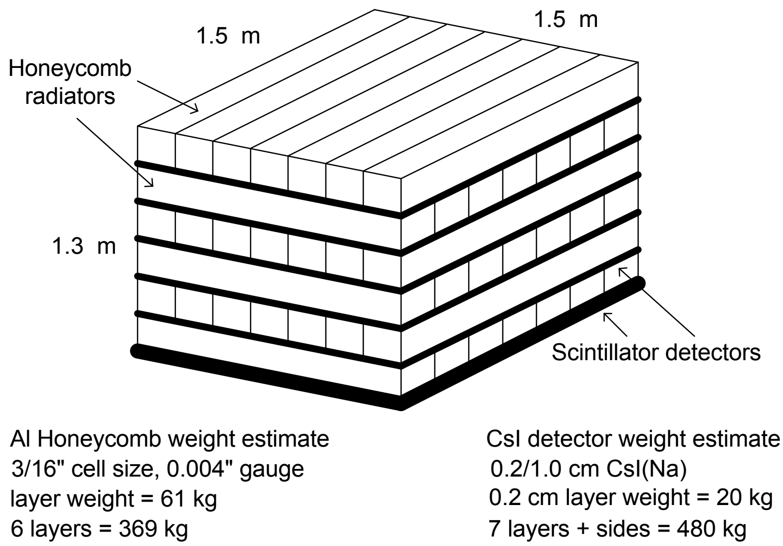

Fig. 3. Schematic of possible ACCESS TRD design. For clarity, the top thick (1 cm) detector layer and side (1 cm) detectors are not shown.

thickness $l_1 \sim 200$ μm therefore appear to be suitable radiator materials (Fig. 4).

The design in Fig. 3 consists of six layers of aluminum honeycomb radiator, each 21 cm deep (corresponding to $N \sim 50$). Each of the first five layers is followed by a 2 mm thick CsI(Na) scintillator. A layer of 1 cm thick CsI(Na) covers the top, bottom, and four vertical sides of the instrument. The thicknesses are chosen as a compromise to maximize the x-ray detection efficiency (including the signal due to "feedthrough" photons in lower layers of the detector stack), minimize the weight, and minimize the probability of particle interactions. Photons with typical energies $\omega_{\max} \sim 175$ keV are detected somewhat inefficiently in each individual detector layer, but then pass through the next radiator and have up to five additional chances to scatter and be detected. The outer layer of 1 cm thick scintillators provides the final chance to detect these feedthrough photons.

The scintillator layers are configured in 0.2 or 1 cm thick × 1.5 cm wide × 1.5 m long strips sandwiched between waveshifting light guides and viewed by 19 mm diameter photomultiplier tubes at each end. The CsI(Na) emission spectrum peaks near 415 nm, and is absorbed and then re-emitted by the waveshifter at a wavelength near 495 nm, where a typical bialkali photocathode has quantum efficiency near 18%. Lab tests have shown an attenuation length with such a configuration of ~160 cm and a photoelectron yield (with ^{57}Co 122 keV x-rays at a distance of 1.25 m from one end) of 15 photoelectrons, compatible with the ACCESS requirements.

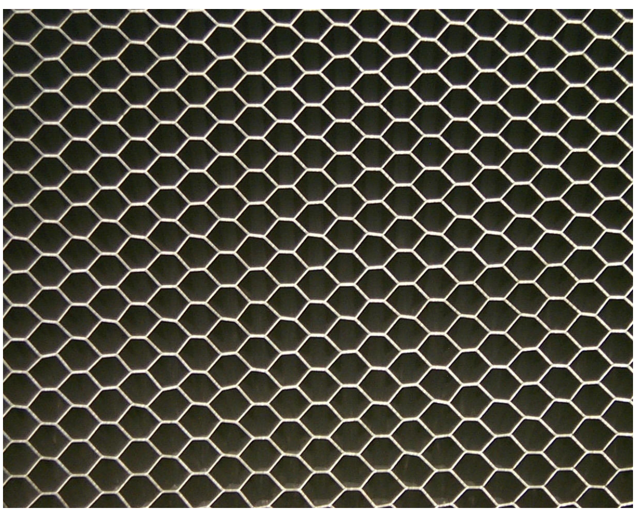

Fig. 4. Aluminum honeycomb radiator material.

Calculated spectra of the produced TR photons (not including absorption, scattering, or detection efficiencies) are shown vs. x-ray energy in Fig. 5 for a set of incident particle Lorentz factors ranging from 5×10^3 to 5×10^5. The frequency spectra clearly illustrate the importance of the response at high x-ray energies and the dependence on Lorentz factor at x-ray energies above 100 keV.

In passing through the multiple radiator and detector layers, 175 keV photons have a significant likelihood of being Compton scattered away from the incident particle trajectory. For the Al honeycomb configuration in Fig. 3, simulations show that up to 50% of the TR photons produced, depending on the particle energy, are Compton scattered out of the 1.5 cm × 1.5 m scintillator strip through which the particle passes. Fig. 6 shows the result of simulations of the TR yield detected as a function of cosmic ray energy for nitrogen nuclei with energies from $\sim 3\times10^2$ to 1×10^6 GeV/nucleon. The simulated detector is 1.5 m on a side, 1.3 m high, and consists of 6 radiator layers each with 50 "foils" (i.e., honeycomb walls) of 8 mil (200 μm) Al separated by 4 mm vacuum gaps. Incident particles are allowed to enter the detector at random positions and random angles ranging from vertically downward to horizontal. A minimum 50 cm pathlength is required through the detector. The scintillators are assumed to be divided into 1.5 cm × 1.5 m strips, and only x-rays detected outside the "beam" strip are counted. The simulation

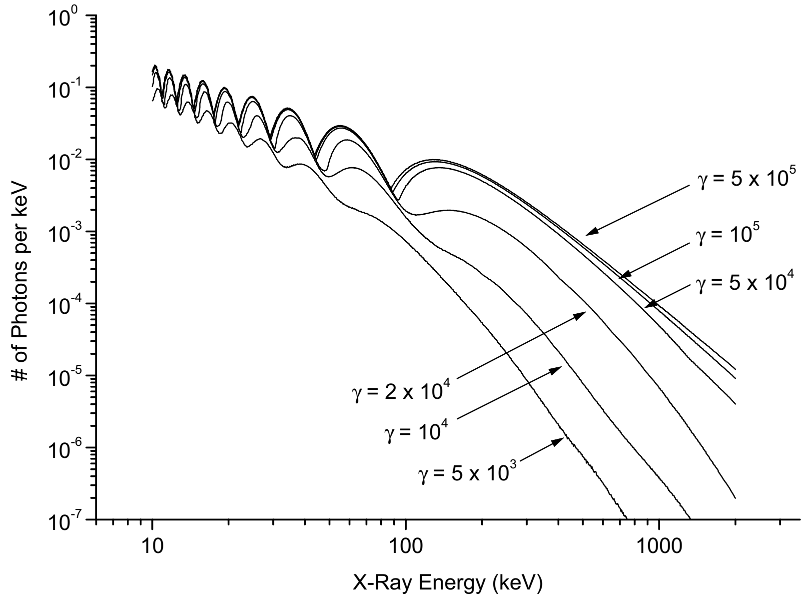

Fig. 5. Calculated transition radiation x-ray spectra for particle Lorentz factors ranging from 5×10^3 to 5×10^5. The radiator consists of 50 aluminum foils ($\omega_1 = 32.8$ eV) of thickness $l_1 = 200$ µm and vacuum gaps ($\omega_2 = 0$ eV) of thickness $l_2 = 4$ mm.

includes the full effects of Compton scattering, absorption, detector efficiencies, and feedthrough.

Final ACCESS designs will depend on the allowed weight, telemetry, power, and cost constraints, which are not yet specified. The current results of both simulations and accelerator tests, however, demonstrate the feasibility of a high energy scintillator design for the ACCESS transition radiation detector.

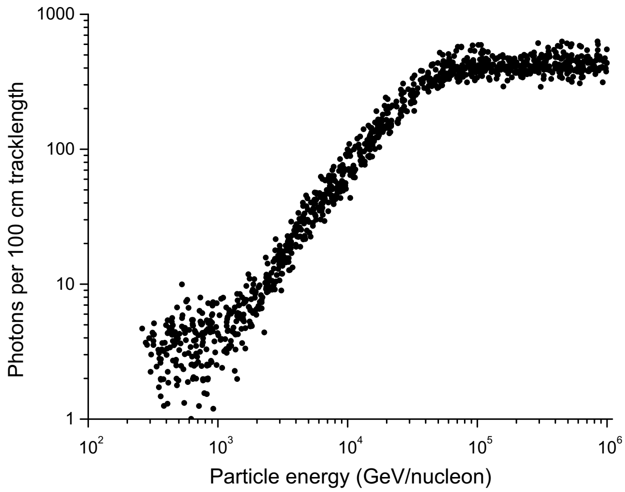

Fig. 6. Results of Monte Carlo simulation of a high energy TRD showing the number of photons detected per 100 cm track length as a function of energy for $Z = 7$ incident particles. The TRD is 1.5 m × 1.5 m × 1.3 m high and consists of 6 radiator layers of 50 aluminum foils each. The individual foil thicknesses are 200 µm with a spacing of 4 mm.

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