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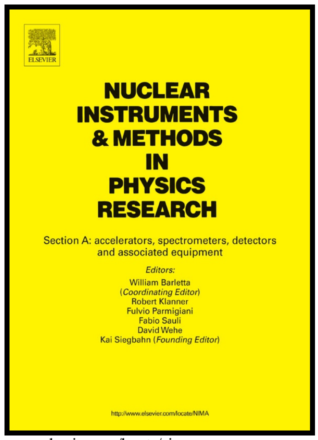

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Radio detection of extensive air showers

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Abstract

Radio detection of extensive air showers initiated in the Earth's atmosphere has made tremendous progress in the last decade. Today, radio detection is routinely used in several cosmic-ray observatories. The physics of the radio emission in air showers is well-understood, and analysis techniques have been developed to determine the arrival direction, the energy and an estimate for the mass of the primary particle from the radio measurements. The achieved resolutions are competitive with those of more traditional techniques. In this article, I shortly review the most important achievements and discuss the potential for future applications.

Keywords:
high-energy cosmic rays, radio emission, extensive air showers

1. Introduction

While the understanding of cosmic rays has progressed very significantly in the last decades, many questions about their origin and the physics of their acceleration are still unanswered [1]. New detection techniques help to maximize the information gathered about each detected cosmic-ray particle. This is especially important at the highest energies where fluxes are extremely low and measurements through air showers yield only rather indirect information on the primary particles. In the last years, radio detection of air showers in the *very high frequency* (VHF) band, typically around 30–80 MHz, has been researched with great effort. Today, the technique has matured from a prototype stage to a well-established detection technique that benefits any cosmic-ray detector in which it is employed. The energy range accessible with the so-far developed approaches is illustrated in Fig. 1

In the following, I give a concise overview of the most important achievements made with the technique to date. For a detailed discussion of the state of the field, I kindly refer the reader to a previously-published extensive review [3].

2. Emission physics

The most important breakthrough of the past few years has been the detailed understanding of the radio emission processes in extensive air showers. Three effects are important:

- Electrons and positrons in the extensive air shower are accelerated by the Lorentz force in the geomagnetic field. At the same time they are decelerated by interactions with air molecules. An equilibrium arises, and the net drift of the particles in directions perpendicular to the air-shower axis leads to transverse currents. As the shower first grows in particle number, then reaches a maximum and then dies out, these transverse currents undergo a time-variation. The time-variation of the currents leads to radio emission. This is the dominant effect responsible for approximately 90% of the electric field amplitude, usually referred to as "geomagnetic emission" [4, 5].
- During the air-shower evolution, a negative charge excess builds up in the shower front. This arises mostly because ionization electrons from the ambient medium are swamped with the shower, while positive ions stay behind. Again, as the shower evolves, the net charge grows, reaches a maximum and then declines. The time-variation of the net charge excess leads to radio emission which contributes approximately 10% of the electric field amplitude. This is the so-called "Askaryan effect" which is the dominant mechanism for radio emission from particle showers in dense media [6, 7].
- At VHF frequencies the radio emission is generally coherent. This means that electric field amplitudes from individual particles add up constructively. The total electric field amplitude thus scales linearly with the number of particles in the air shower, which in turn scales approximately linearly with the energy of the primary cosmic ray. Consequently, the radiated power (and energy) scales quadratically with the cosmic-ray energy. Coherence is governed by different scales in the air shower: the thickness of the shower pancake, the lateral width of the shower, and the time-delays arising from the geometry of the shower disk propagating with the speed of light as seen from a specific observer location. The latter is strongly influenced by the refractive index of the air which is approximately 1.0003 at sea level and scales with the density gradient of the atmosphere. This leads to "Cherenkov rings" in the radio-emission footprints; observers on these rings see time-compressed radio signals for which coher-

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