Radio emission from cosmic ray air shower via Inverse Compton Scattering

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***Abstract*. Radio emission of Extensive Air Shower is described as the result of anisotropic Inverse Compton Scattering of the virtual photons of the static geomagnetic field by the shower electrons with energy γmc^2. The equivalence of synchrotron radiation and Inverse Compton is known since a long time and has been demonstrated fifteen years ago by Lieu and Axford. In the electron rest frame, static field is seen as a burst of Lorentz boosted photons with cyclotron frequency $\gamma h\nu_0$. In this frame they are scattered according to Thomson limit since their energy is still small compared to electron mass. The radiative power is obtained from a Lorentz transformation of scattered photons back to the static frame. The photons are then shifted up to a maximum frequency of $4\gamma^2 h\nu_0$ in the isotropic case. This simple approach leads to a rather good representation of the radio emission properties. It does not substitute to the usual synchrotron calculation from retarded potentials, but provides a handy model to be used in debugging radio detection experiment. When adapted to an air shower fast simulation code including an electron energy spectrum, this method can be used as a guide to infer the shower parameters from the radio observables. The radiation frequency spectrum, lateral extension, intensity and signal time profile at detection site, as well as their correlations can be easily obtained. At a given location distance, the signal time profile is clearly correlated to the longitudinal shower development; the evolution of this correlation curve for different observation distances indicates a pathway to recover shower profile. The effect of the narrow frequency detection band on the shower radio image and its effects on the sensitivity range and acceptance is shown. Geomagnetic and polarization properties of the radiated photons are intrinsically included in this approach, while a complete calculation of the scattering in term of the electromagnetic tensor would need a more refined investigation from a theoretical point of view than the one developed here. This work is in progress.**

***Keywords*: radio,cosmic,shower**

I. INTRODUCTION

The description of the interaction of electrons with photons in term of Compton scattering is a process widely used in various fields from astrophysics to laser physics for example. While passing through an isotropic bath of photons, an electron of energy γmc^2 looses energy transferring it to photons. Photons are then backscattered in the electron direction of motion and boosted by a factor of $4\gamma^2$ [1]. In presence of a very high energy electron beam, thermal or optical photons can be boosted to X-ray or γ-ray in stellar environment. While Inverse Compton Scattering (ICS) is mostly used to describe the interaction of electrons with real photons, it was also developped long time ago by Fermi to interpret the bremmstrahlung emission in term of scattering of electrons on the virtual photons associated with the electric field of a nucleus. In presence of a magnetic field the synchrotron emission, sometimes called 'magnetic bremmstrahlung', was thought to be interpreted in term of ICS on the virtual photons of the static magnetic field. It was noted since a long time that the synchroton emitted power formula,is identical to the one expressed via ICS, replacing the magnetic field energy density term by a photon energy density. However it took a certain time for ICS interpretation to overcome some conceptual difficulties concerning the continuous character of the synchrotron emission and mainly the fact that in presence of a magnetic field, the electron is submitted to a force implying the electron rest frame not to be inertial, then the Lorentz transformation laws of the electromagnetic tensor are not applicable. The contradiction was solved by Lieu & Axford [2] who considered the interaction within infitesimal time slabs where the electron rest frame can be considered as inertial, and they added coherently the successive scattering amplitudes along the track.

In this paper we propose to apply the ICS method to describe the interaction of the photons associated with the geomagnetic field with the electrons produced in cosmic ray extensive air showers (EAS) in the earth atmosphere. The scattered photons boosted in the radio frequency domain constitute the radio emission associated with an EAS.

II. INVERSE COMPTON SCATTERING KINEMATICS

Considering the interaction of a photon with energy ϵ and a relativistic electron with Lorentz factor γ and a velocity β with a relative direction of motion given by an angle α, the ICS treatment consists in the transformation to electron rest frame; in the frame where the electron is at rest, the photon diffuses via compton scattering and then is transformed back to the static frame. The two successive transformations with each a lorentz factor γ, will gives to the outgoing photon a boosted energy by a factor up to $4\gamma^2$. The photon energy in the rest frame

of the electron is $\epsilon' = \gamma\epsilon(1 - \beta cos\alpha)$ In scattering off the electron in rest frame, the photon goes off at an energy ϵ'_1 in usual compton energy shift formula. When the condition $\epsilon' << mc^2$ is realized, there is no energy shift and the scattering occurs in the Thomson limit. The total scattering rate and the emitted radiation power are governed by the Thomson cross-section σ_T then $dE/dt = \sigma_T c \int (1 - \beta cos\alpha)^2 \epsilon dn$ where dn is the initial photon number density. In the isotropic photon case the integration leads to well known $dE/dt = 4/3\sigma_T c\gamma^2 n_{iso}$ formula. In the present case the photons propagate in the unique direction of the magnetic field and the anisotropic formula must be kept; the photon energy density is equivalent to the magnetic field energy density $\epsilon dn = B^2/8\pi$

Following Blumenthal and Gould [1] the derivation of the spectrum of the compton scattered photons can be obtained. The distribution in energy and angle is taken in the electron rest frame, and with the proper transformation invariants, the photon spectrum is derived to $dN/dtd\hat{\epsilon} = 8\pi r_0^2 cnd\hat{\epsilon}f(\hat{\epsilon})$ where here $\hat{\epsilon}$ is the relative energy to the maximum $\epsilon_{max} = 4\gamma^2\epsilon$. While for high energy photons the function f peaks toward the highest values, it peaks at very low values in the the Thomson limit case. At last, the compton scattered photon at an
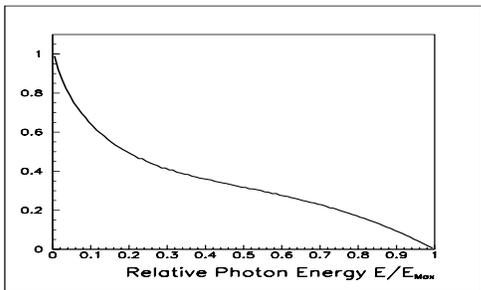

Fig. 1: Scattered photon distribution function $f(\hat{\epsilon})$ in the Thomson limit.

angle θ' in the electron rest frame are transformed back to the observer frame. Due do Lorentz focussing photons are observed within a cone of aperture θ around the electron direction with $\tan\theta = \gamma^{-1}sin\theta'/(cos\theta' + \beta)$. When $\gamma >> 1$ the opening angle is narrowed to $\theta \approx \gamma^{-1}$.

III. PHOTONS AND ELECTRONS SPECTRA

A. *Virtual photons of the static magnetic field*

In the instantaneous moving electron rest frame, the lorentz transformation of the static magnetic field leads to the apparition of an electromagnetic burst or photons with an energy $\hbar\omega = \gamma\hbar\frac{e}{m}B_\perp$. The initial virtual photons in the static frame had an initial energy equal governed by the cycloton frequency ω_0 characteristic of the electron motion under the presence a magnetic field. Only the transverse component of the magnetic field contributes to the boosted electromagnetic Lorentz transform to the electron frame. At this step, one can observe that when the magnetic field direction is colinear to the electron frame motion, the associated virtual photons will have a null energy contribution to the scattering. The basic frequency of the virtual photons can be written as $\omega_0 = \frac{e}{m}B_0\sin\alpha$ were α is the geomagnetic angle of the electron motion. Whatever the electron energy, one can already predict a geomagnetic suppression of the radio emission when electron motion is colinear with the magnetic field; this effect comes from the lorentz transformation properties.

B. *The Air Shower as electron beam*

Electrons (and positrons) are the most abundant particles created in an EAS. The EAS can then be considered as an electron beam whose intensity varies according to the longitudinal development of the shower, reaching a maximum at X_{Max}. This electron beam is not monochromatic but its energy spread is related to electron energy spectrum within the shower. This spectrum has been studied from air shower simulations and has been shown to be rather universal since independant on shower energy, cosmic ray nature and very slightly dependent on shower age [3]. This energy spectrum decreases rapidly
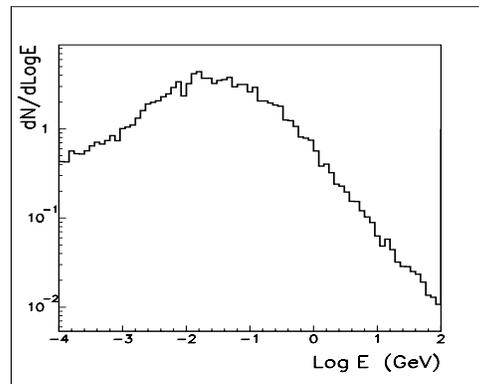

Fig. 2: Shower Electron energy spectrum

from below MeV range energy to high energies with a mean value between 20 and 30 MeV. Such an electron spectrum used here to describe the photon-electron collision at each step of the EAS development. The electron multiple scattering was not yet taken into account in the following description, andshould be developped in a further step.

IV. AIR SHOWER RADIO EMISSION CHARACTERISTICS FROM ICS

The present fast monte-carlo simulation parametrized the longitudinal shower development by a function 'à la Hillas'. The emitted radiation is the result of ICS of the virtual photons on each electron of the shower.It mainly results in a convolution of the electron energy spectrum 2 with the scattered photon spectrum 1, together with the longitudinal shower profile. The intensity of radiation is obtained without any normalization factor.

A. Geomagnetic effect

A numerical value can be extracted at the observation site of the shower. In Northern hemisphere at a geodesic location (47N,2E),the geomagnetic field point downward to ground in the northern direction at a zenithal angle of $27°$ with a magnitude $B_0 = 47\mu T$ corresponding to a vitual photon frequency of $\nu_0 \approx 1.3MHz$ ($\epsilon = 5.4810^{-9}eV$). While in southern hemisphere,i.e at Auger site (35S,69W), the field points upward to north at a zenithal angle of $50°$with a weaker magnitude corresponding to photon frequency of $\nu_0 \approx 0.7MHz$. The predicted geomagnetic suppression in both sites is shown in figure 1. This is confirmed by experimental results from CODALEMA in Nancay [5] and from radio detection at the Pierre Auger Observatory [6].
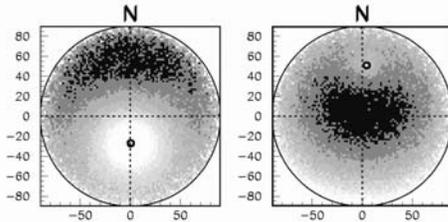

Fig. 3: Radio emission asymetry as a function of shower angle. Northern hemisphere at left, Southern at right

B. The Frequency spectrum

The maximum frequency of the scattered photons can reach hundreds of GigaHertz due to the γ^2 boost. The integrated power below 100 MHz, where the radio emission magnitude is above the natural background, represents only a small fraction of the total emitted power. Moreover the frequency spectrum is sensitive to the relative shower angle with respect to the magnetic field.
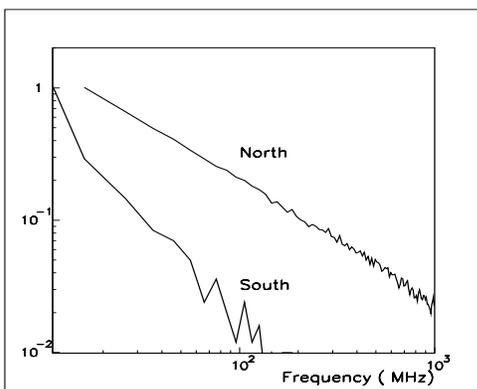

Fig. 4: Radio emission frequency spectrum for a $10^{17}eV$ shower at a zenith angle $\theta = 30°$. North and South azimuth are shown.

C. The radiation Electric field

The ICS method handle with photons then in terms of the radiation power. The radio observation, mostly realized with dipole antenna,is sentitive to the radiation electric field. In the proposed scheme the electric field associated to the incoming virtual photons is aligned with $\vec{\beta} \otimes \vec{B}$, from the Lorentz transformation. It was shown that the polarization was mostly conserved in Thomson scattering and at a 80% level in the global ICS process [4]. This subject represent a wide field of study which extend beyond the present work, and we shall assume here the conservation of the polarization in considering that the product of incoming and outgoing polarizations is an invariant under Lorentz transform. In the following we shall consider only the magnitude of the electric field extracted from the Poynting vector $P = E^2/4\pi$.

D. The Lateral Distribution

Photons are emitted within a cone around the shower. Each photon scattered from an electron with a lorentz factor γ within vertical shower at an elevation x will impact at ground at a distance from the shower core $r = x \cdot tan(1/\gamma)$. Summation over the shower profile and the electron spectrum generate the lateral distribution function. Since the emission is the result of the
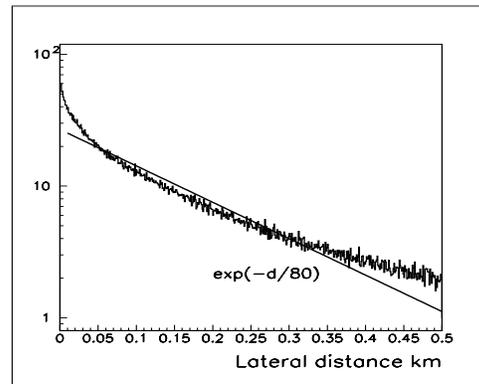

Fig. 5: Lateral distribution in full frequency band. The slope parameter d_0 is obtained by fitting with a single exponential function within the [50,500] meters range
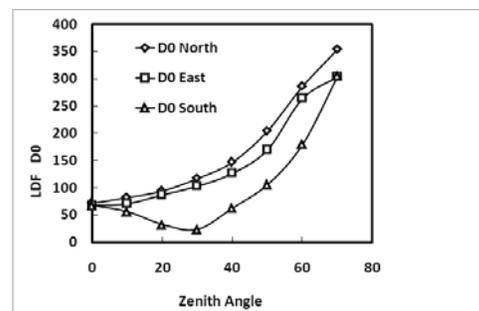

Fig. 6: Single exponential slope paramater dependence with shower zenith angle for different azimuth in the [20,80]MHz band

convolution of the electron spectrum and the photon compton scattering spectrum which are far from single

exponential shape, the resulting lateral distribution cannot present a single exponential shape. At most, several exponential curves can be used to fit the resulting distribution according to the considered range of detection distance. However a ldf slope was extracted from a single exponential fit in the [50,500] meters range. It presents several characteristics shown in figure 6 for $10^{17}eV$ shower.

E. Signal shape and time spectrum

The signal time shape is estimated here for a shower with $E = 10^{17}eV$ coming from north at $\theta = 30°$. Within a filtered frequency band [20,80] MHz the signal time profile obtained at a distance of 100 meters from shower core is shown on left part of figure 7. The signal amplitude is integrated in the 60 MHz bandwidth, corresponding to $E \approx 2.5\mu Volts/m \cdot MHz$ as expected from other results at this energy. The signal is very fast lasting few nanoseconds. At fixed angle and within a frequency band the signal amplitude scales linearly with shower incident energy. This signal time profile is shown as a function of lateral distance on the right hand side. The envelop of maxima follows a semi-parabolic law as the distance increases. Such a behaviour is not the expression of a spherical wave front, but results from the successive emission time within the shower observed with a varying delay time at different positions.
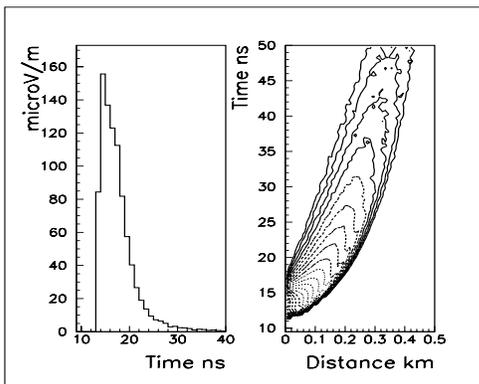

Fig. 7: Signal time profile at 100 m (left). Evolution of the signal time profile as a function of the distance from shower core (right)

From the experimental measured spectra one could have expected to infer some information about the shower itself. Since most of the emission parameters (frequency,lateral distribution and magnitude) are strongly intricated, a geometrical information about the shower development has been thought to be extracted from the arrival time of the signal at the observer location. This time of arrival beeing governed only by the distance from the emission point to the observer, it should be sensitive to longitudinal shower profile and then to the X_{max} position. A relation between the signal arrival time and altitude of the emission point is represented in figure 8 for various distance of

detection. A clear correlation exists between both quantities, however the hyperbolic shape of the correlation curve will prevent any single bijective relation between those parameters. To the arrival time at given distance presented on the x-axis, corresponds a rather wide band of emission altitude, except at large distances. This is the consequence of the lorentz boosted radio emission when compared to the isotropic distribution of fluorescence emission.
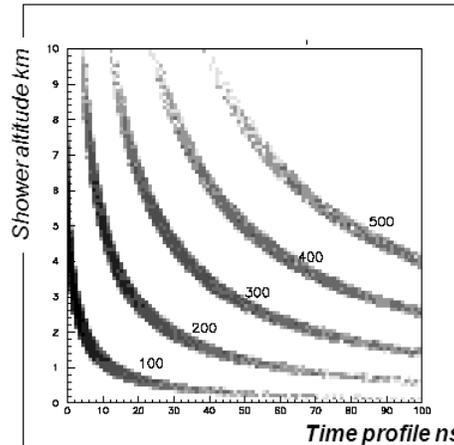

Fig. 8: Emission point altitude as a function of signal arrival time for different distances from shower core

V. CONCLUSIONS

ICS allows to reproduce and predict many characteristics of the shower radio emission. Once the concept of the virtual photon associated with the magnetic field is admitted, only relativistic kinematics of the interaction $e - \gamma$ is needed. Very low energy virtual photons of the static geomagnetic field (of the order of 1 MHz), are boosted to high energies in the electron rest frame where they are scattered Inside a shower, electrons have a rather low energy, so the emitted radiation is dominant for MHz frequency range but the main radiation power is found up to high frequencies. The Lorentz transformation of the electromagnetic field, where only transverse component are boosted, leads to specific pattern of the radio emission relative to the magnetic field. These effects where already observed experimentally. The shower parameters such as longitudinal profile can be extracted with care due to the lorentz distorted shape of the radio emission at the observer position.
Work is underway to include more refined description of the process, including the radiation polarization not developped here.

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