On the RADAR detection of high-energy cosmic neutrinos in ice

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Abstract. We discuss the radar detection technique as a method for the detection of high-energy cosmic-neutrino-induced particle cascades in ice. When propagating through the ice, the high-energy particles in the cascade will ionize the medium and induce a plasma. Different properties of this plasma, such as its lifetime and charge density, are discussed. Using these properties, we first give an estimate for the energy threshold for the over-dense radar scattering off of the plasma. Furthermore, using the different properties of the plasma and the medium, an estimate is made for the radar return power as a function of detection distance.

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INTRODUCTION

Recently the IceCube neutrino observatory for the first time detected high-energy cosmic neutrinos [1]. At the highest energies these cosmic neutrinos become very rare. At energies above several PeV, IceCube runs out of statistics, where only at EeV energies the currently operating Askaryan radio detectors [2, 3] start to become sensitive. This leaves an energy gap in the PeV to EeV region. In [4], we discussed the radar detection technique as a possible method to fill this energy gap.

The radar detection technique is currently already under investigation for the detection of cosmic-ray air showers [5-15], but no detection has been confirmed so-far. More recently suggestions were made to measure the reflection of radio waves from high-energy neutrino-induced particle cascades in rock salt and ice [4, 16].

When a high-energy cosmic neutrino interacts in ice, a particle cascade can be induced. When propagating through the ice, the high-energy particles in the cascade will ionize the medium. Following experiments performed around the 1980's [17-20], we consider two different constituents of the induced ionization plasma. Next to a rather short-lived electron plasma, a longer-lived plasma with its characteristics corresponding to a heavier constituent comparable to free protons was observed in these experiments. Considering the lifetimes and properties of these plasmas, an energy threshold for the over-dense scattering of a radio wave off of the plasma has been estimated. For the electron plasma this threshold was estimated to be 4 PeV measuring at 1 GHz, where for the proton plasma a value of 20 PeV was found for a sounding frequency of 50 MHz. Next to this, we determined the radar return power as a function of detection distance for several different geometrical configurations. It was found that both the electron as well as the proton plasma should be detectable at distances between a few hundred meters for a non-ideal geometry, up to several kilometers for more favorable geometries. It follows that the radar detection method is a very promising technique for the detection of high-energy cosmic neutrinos, probing the currently existing energy gap between several PeV and a few EeV.

In this article we shortly recall the different properties of the plasma and the determination of the energy threshold. In the following the radar return power calculations will be treated in more detail. Where in [4] a very conservative estimate was made for the radar return power, in this article we open up the parameter space by discussing the return power considering the different uncertainties on several parameters such as the attenuation length, the noise floor, and the lifetime of the plasma.

THE PLASMA

The over-dense scattering off of a plasma is defined by the condition that the sounding frequency is smaller than the plasma frequency $\nu < \nu_p$. Nevertheless, to scatter off of a plasma with a finite lifetime τ_p and dimension l_c, the plasma should be able to make a full oscillation. Leading to the condition,

$$\nu_p > \nu \quad > \quad \begin{cases} 1/\tau_p & (c_{med}\tau_p < l_c) \\ c_{med}/l_c & (c_{med}\tau_p > l_c) \end{cases} \tag{1}$$

Where c_{med} is the speed of light in the medium. Hence, we obtain a lower limit for the plasma frequency. Now looking closer into the definition of the plasma frequency,

$$\nu_p = 8980\sqrt{\frac{m_p}{m_e}}\sqrt{n_p}\ \text{Hz}, \tag{2}$$

the plasma frequency scales directly with the free charge density n_p of the plasma. Where for a charge with (effective) mass m_p, a correction has to be made with respect to the electron mass m_e. In [4], it is shown that the free charge density scales directly with the energy of the primary cascade inducing particle giving,

$$\nu_p = 0.5\sqrt{\frac{m_p}{m_e}}\sqrt{E_p[\text{GeV}]}\ \text{MHz}. \tag{3}$$

In Eq. 1, a lower limit for the plasma frequency was obtained in case of the over-dense scattering off of the plasma. Hence this condition immediately gives a lower limit on the energy of the primary cascade inducing particle, determined by either the lifetime of the plasma or the dimensions of the plasma.

In [4], it is shown that the longitudinal dimension of the plasma tube corresponds to approximately 5-10 m for primary cascade inducing particles with energies in the PeV to EeV range. For the lifetime of the plasma we based ourselves on measurements given in [7-20]. For the electron plasma, a lifetime is found of approximately 100 ps at high temperatures close to freezing point to several tens of nanoseconds at temperatures of $-60°$ Celsius. Even-though the ice temperatures at the South-Pole are relatively low of the order of $-50°$ Celsius, in [4] we assumed a conservative value for the electron lifetime $\tau_e = 1$ ns. Next to the electron plasma, a long-lived plasma with its properties equal to free protons was observed. The lifetime of this hereafter named proton plasma was found to be of the order of tens of nanoseconds to several microseconds.

For the proton plasma, it can be calculated that the size of the cascade is the limiting factor. Taking $l_c = 5$ m, in [4] a lower limit for the plasma frequency of 36 MHz was obtained, leading to an energy threshold of approximately 20 PeV. Considering the electron plasma, the limiting factor was the lifetime of the plasma which was conservatively taken to be 1 ns, leading to an energy threshold of approximately 4 PeV for a sounding frequency of 1 GHz.

RADAR RETURN POWER

In [4] we considered the radar return power for both the electron plasma as well as the proton plasma. In calculating the radar return power several parameters were fixed rather conservatively. In this section we discuss these parameters and as an example consider two different situations at both the conservative end of the parameter space, as well as the progressive side of the parameter space. Following [4], the radar return power for a bi-static radar configuration is given by,

$$P_r = P_t\eta\frac{\sigma_{eff}}{\pi R^2}\frac{A_{eff}}{4\pi R^2}e^{-4R/L_\alpha}. \tag{4}$$

Here we consider a symmetric configuration such that the distance R from the emitter to the cascade is equal to the distance from the cascade to the receiving antenna. The different parameters in this equation are given in Table 1. An overall efficiency factor of $\eta = 0.1$ is used to take into account for possible effects that have been ignored so-far. For the radar cross-section, we base ourselves on a thin wire approximation used in [6, 21]. Logically, the radar cross-section is a function of the dimensions of the plasma tube and the detection frequency. Where for the proton plasma, the dimensions are dominated by the length of the cascade, for the electron plasma this is only the situation for the longest lifetimes of several tens of nanoseconds measured at temperatures below $-50°$ Celcius. In this situation, the detection frequency is chosen to be $\nu = 50$ MHz for both the electron as well as the proton plasma. On the conservative

TABLE 1. Parameters used to determine the radar return power and the noise power.

	Description	Value
η	Efficiency factor	0.1
$\sigma^e_{eff}(\nu = 0.05 - 1\ \text{GHz}, \theta = 0° - 60°, \phi = 0° - 60°)$	Electron plasma radar CS	$1.6 \cdot 10^{-4} - 5.5\ \text{m}^2$
$\sigma^p_{eff}(\nu = 50\ \text{MHz}, \theta = 0° - 60°, \phi = 0° - 60°)$	Proton plasma radar CS	$1.2 \cdot 10^{-2} - 5.5\ \text{m}^2$
$L^e_\alpha(\nu = 0.05 - 1\ \text{GHz})$	Attenuation length at the South-Pole	313-1500 m
$L^p_\alpha(\nu = 50\ \text{MHz})$	Attenuation length at the South-Pole	800-1500 m
T_{sys}	System temperature	325 K
$\Delta\nu$	Detection band-width	0.1-10 MHz

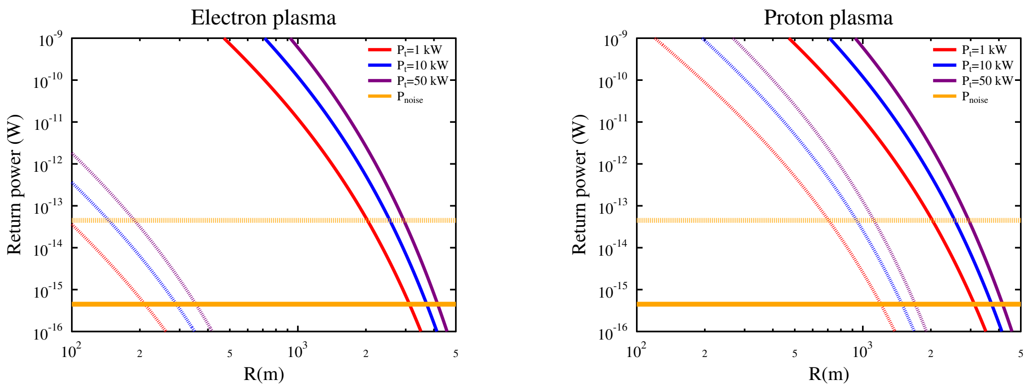

FIGURE 1. The radar return power as a function of the source distance for the electron plasma (left) and the proton plasma (right). The return power is given for two different situations, the most conservative approximation shown by the dashed lines and a more progressive estimate given by the full lines.

side a lifetime of 1 ns is considered for the electron plasma. In this situation, the detection frequency has to be in the GHz range, and the dimensions of the plasma are dominated by its lifetime. Furthermore, the radar cross-section depends strongly on the polarization angle θ and incident angle ϕ of the incoming wave. The attenuation length is determined by measurements performed by the ARA collaboration at the South-Pole [2]. On the progressive side we use the attenuation length measured at the South-Pole within the first 1500 m of the ice-sheet at a frequency of 300 MHz, which was found to be around 1500 meters. On the conservative side, assuming a low detection frequency of 50 MHz, we took the all-ice value of 800 m as measured by the ARA collaboration at a frequency of 300 MHz. For a high detection frequency of 1 GHz, we use an extremely conservative value for the attenuation length of 313 m which is observed at the Ross ice-shelf [22]. The noise floor accordingly is dominated by thermal noise and given by $P_{noise} = k_B T_{sys} \Delta\nu$, where the system temperature $T_{sys} = 325$ K is chosen following measurements at the ARA site, k_B is Boltzmann's constant and the detection band-width is estimated to lie in between 100 kHz and 10 MHz.

Results

As was already shown in [4], from Fig. 1 it follows that even in the most conservative situation, for the electron plasma which is being probed under a highly non-ideal geometry, the return power lies above the background for source distances up to a few hundreds of meters. The total distance covered by the received signal is twice the source distance since we consider a symmetric situation where the distance from the transmitter to the plasma R is equal to the distance from the plasma to the receiver. Considering the proton plasma, this distance increases to several kilometers already in the most conservative approximation. For the more ideal situation considering more progressive parameter values the return power lies above the background for source distances of a few kilometers for both the proton plasma as well as the electron plasma. It follows that the radar detection method is a very promising technique for the detection of high-energy cosmic neutrinos, probing the currently existing energy gap between several PeV and a few EeV.

Discussion and Outlook

As can be seen in Fig. 1 it follows that there is a large difference in the return power calculations using different parameters for the electron plasma. This is mainly due to the uncertainty in the lifetime of the plasma, which for the conservative estimate of $\tau_e = 1$ ns determines both the size of the plasma as well as the sounding frequency, and therefore directly lead to a smaller radar cross-section and a decreasing attenuation length. In [17-20], it was shown that the lifetime of the electron plasma is strongly dependent on the purity and temperature of the ice. Therefore, new experimental results on the lifetime of the electron plasma using ice from a natural ice-sheet at temperatures comparable to those found at the South-Pole are highly favorable. For the proton plasma, the smallest lifetimes are long compared to the dimensions of the plasma and therefore the conservative and progressive estimate for the return power are closer to each other. The main difference here is due to the non-ideal geometry considering a polarization angle $\theta = 60^\circ$, and the angle of incidence $\phi = 60^\circ$, in the conservative estimate with respect to zero polarization and normal incidence in the progressive estimate.

Another uncertainty is the band-width which can be used to detect the scattered signal. Even-though technically it is possible to have a small band-width of the order of 100 kHz, several effects are currently still under investigation. One of these effects is the possible frequency up-shift of the scattered signal due to the relativistic movement of the cascade itself. In this situation it might be preferable to detect over a wider band-width, which is a technical challenge. One approach to solve for the scattering including a more realistic particle distribution is a FDTD approach, where Maxwell's equations are solved on the grid. Currently a study is being performed to use the MEEP-code [23] to perform these calculations. If successful, this should allow us to model both the over-dense scattering as well as the under-dense scattering cross-checking and improving on the currently employed analytical approaches.

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