Radar detection of high-energy neutrino induced particle cascades in ice

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IceCube sensitive below several PeV

Motivation

Sensitivity Gap in PeV – EeV region

Askaryan Radio detectors become sensitive close to the EeV region

Radar?

M. Abou Bakr Othman et al, Proceedings 32nd ICRC, Beijing 2011
Radar scattering of a neutrino induced plasma

Leftover electrons from ionization:
Extension: $O(30 \text{ cm})$
Lifetime: $O(1\text{-}20 \text{ ns})$

Shower front electrons:
Extension: $R_L = O(10 \text{ cm})$
Lifetime: $O(100 \text{ ns})$
Moving!

Leftover protons from ionization:
Wide extension: $O(5 \text{ m})$
Lifetime: $O(10\text{-}1000 \text{ ns})$

Ionization numbers come from Physical Chemistry research!

Figure from arXiv:1210.5140v2
RADAR scattering

- **Over-dense scattering:**
  - Radar frequency < Plasma Frequency
  - Reflection from the surface of the plasma tube

- **Under-dense scattering:**
  - Radar frequency > Plasma Frequency
  - Scattering off of the individual charges in the plasma
RADAR return power estimation

Bi-static RADAR configuration

Effective area of receiver: $A_{\text{eff}}$

Transmitted power: $P_t$

Transmission over $\frac{1}{4}$ of a sphere: $\frac{1}{(\pi R^2)}$

Re-scattering over a sphere: $\frac{1}{(4\pi R^2)}$

Plasma scattering surface: $\sigma_{\text{eff}}$

Attenuation by the medium

$$P_r = P_t \eta \frac{\sigma_{\text{eff}}}{\pi R^2} \frac{A_{\text{eff}}}{4\pi R^2} e^{-4R/L_\alpha}$$
RADAR return power estimation (single antenna)

\[ P_r = P_I \eta \frac{\sigma_{\text{eff}}(\lambda)}{\pi R^2} \frac{A_{\text{eff}}(\lambda)}{4\pi R^2} e^{-4R/L_\alpha} \]

\( \lambda = 0.18 \text{ m} \)
\( \sigma_{\text{eff}}^{\text{max}} = 0.11 \text{ m}^2 \)
\( \sigma_{\text{eff}}(\theta = 60^0, \phi = 60^0) = 1.6 \cdot 10^{-4} \text{ m}^2 \)
\( L_\alpha = 1 \text{ km} \)
\( P_{\text{noise}} = k_b T_{\text{sys}} \Delta \nu \)
\( T_{\text{sys}} = 325 \text{ K} \)
\( \Delta \nu = 100 \text{ kHz} \)

N antennas:
\( P_{\text{Noise}}(N) = N \cdot P(N = 1) \)
\( P_{\text{Signal}}(N) = N^2 \cdot P(N = 1) \)

\( E > 4 \text{ PeV} \)
RADAR return power estimation (single antenna)

\[ P_r = P_t \eta \sigma_{\text{eff}}(\lambda) \frac{A_{\text{eff}}(\lambda)}{\pi R^2} \frac{e^{-4R/L_\alpha}}{4\pi^2} \]

\( \lambda = 3.6 \text{ m} \)
\( \sigma_{\text{eff}}^{\text{max}} = 5.5 \text{ m}^2 \)
\( \sigma_{\text{eff}}(\theta = 60^0, \phi = 60^0) = 1.2 \cdot 10^{-2} \text{ m}^2 \)
\( L_\alpha = 1.4 \text{ km} \)

\( P_{\text{noise}} = k_b T_{\text{sys}} \Delta \nu \)
\( T_{\text{sys}} = 325 \text{ K} \)
\( \Delta \nu = 100 \text{ kHz} \)

\( N \) antennas:
\( P_{\text{Noise}}(N) = N \cdot P(N = 1) \)
\( P_{\text{Signal}}(N) = N^2 \cdot P(N = 1) \)

Proton plasma

E > 20 PeV
RADAR return power estimation (single antenna)

\[ P_r = P_t \eta \frac{\sigma_{\text{eff}}(\lambda)}{\pi R^2} \frac{A_{\text{eff}}(\lambda)}{4\pi R^2} e^{-4R/L_\alpha} \]

\[ \lambda = 2.6 \text{ m} \]
\[ \sigma_{\text{eff}} = 5.5 \text{ m}^2 \]
\[ \sigma_{\text{eff}}(\theta = 60^0, \phi = 60^0) = 1.2 \cdot 10^{-2} \text{ m}^2 \]
\[ L_\alpha = 1.4 \text{ km} \]
\[ P_{\text{noise}} = k_b T_{\text{sys}} \Delta \nu \]
\[ T_{\text{sys}} = 325 \text{ K} \]
\[ \Delta \nu = 100 \text{ kHz} \]

N antennas:
\[ P_{\text{Noise}}(N) = N \cdot P(N = 1) \]
\[ P_{\text{Signal}}(N) = N^2 \cdot P(N = 1) \]

\[ E > 20 \text{ PeV} \]
Open questions: The Plasma

- How large is the over-dense plasma?
- What is the influence of skin-effects?
- What is the lifetime of the plasma?
- Is the plasma collision frequency low enough?

Experimental verification needed!
Radar scattering experiment at TA-ELS

Many thanks to the Chiba group and the Telescope Array Collaboration!
Experimental setup
Experimental setup

Channel 1, 3 Receivers
Channel 2 Transmitter
Antenna geometry used for
ELS beam tests on Sunday
January 11, 2015

DESCRIPTION
ELS Rooftop Geometry 20150111

Early Configuration

Later Configuration
Signal chain

**Tx Chain**

MiniCircuits SSG-6000RC RF Synthesizer → MiniCircuits Power Splitter ZX10R-14-S+ → +35 dB → 120' LMR-400

**Rx Chain**

Agilent 9254 MSO 2.5 GHz → +15 dB → 120' LMR-400
Radar scattering
Beam characteristics

\( \sim 10^9 \) (40 MeV) electrons
\( \sim 40 \) PeV
Radar scattering
What do we see?

Raw time trace

- Tx leaking into Tr
- Klystron noise
- Askaryan + Transition radiation signal
Radar scattering
What do we see?

1) Tx leakage
2) Klystron+Tx / Non-linear amp
3) Direct signal + Radar reflection?

V/Hz(1.55 GHz)

Time (100 ns bins)
Radar scattering
Interference and instrumental effects

- Accelerator noise interferes with our transmit signal

- Non-linear amplifier response

- Signal can be mimicked by these effects!

- What if we look at a different frequency than our transmit frequency?
Radar scattering
Air

No scaling observed

Accelerator background
Radar scattering

Ice

Scaling with input power

Accelerator background
Conclusions

- Modeling the RADAR scattering of high-energy neutrino induced cascades gives an energy threshold of several PeV.

- We performed a measurement to determine the feasibility of this method.

- Obtained data hints toward a scattered signal, analysis is ongoing.
New detection method

If a RADAR signal can be bounced off of a neutrino induced cascade in ice, we have control over the signal strength!

M. Abou Bakr Othman et al, Proceedings 32nd ICRC, Beijing 2011

Infrastructure already available!
Over-dense scattering

\[ \nu_{\text{Plasma}} > \nu_{\text{Radar}} > \begin{cases} \frac{1}{\tau_{\text{Plasma}}} & c_{\text{med}} \tau_{e} < l_{c} \\ \frac{c_{\text{med}}}{l_{c}} & c_{\text{med}} \tau_{e} > l_{c} \end{cases} \]

\[ \nu_{\text{Plasma}} \propto \sqrt{n_{\text{Plasma}}} \propto \sqrt{E_{\text{primary}}} \]
Skin Effects

Model: Consider over-dense cylinders of equal density

Calculate skin depth for a collision less plasma:

\[ \delta = \frac{c}{2\omega_p} \]

Within 1 skin depth the amount of power absorbed and re-scattered equals:

\[ f_{\text{skin}}^{i+1} = (1 - f_{\text{skin}}^i)(1 - e^{-\frac{x}{\delta_i}}) \]
The over-dense radar cross-section

This approach:

1. Include skin-effects directly into the radar cross-section.
2. Consider projected area and polarization angles for in/out-going wave

\[
\sigma_{od} = A_{\text{plasma}} \times f_{\text{skin}} \times f_{\text{geom}}
\]

\[
A_{\text{Plasma}}^i \approx L_i r_i
\]

\[
f_{\text{skin}}^{i+1} = (1 - f_{\text{skin}}^i)(1 - e^{-x/\delta_i})
\]

\[
f_{\text{geom}} = (\vec{e}_t \cdot \vec{e}_c)(\vec{e}_c \cdot \vec{e}_r)
\]

\[
\sigma_{od} = \sum_i L_i r_i (1 - f_{\text{skin}}^i)(1 - e^{-x/\delta_i})(\vec{e}_t \cdot \vec{e}_c)(\vec{e}_c \cdot \vec{e}_r)
\]
The under-dense radar cross-section

The wave will scatter off of the individual electron given by the Thompson cross-section

$$\sigma_T = \left( \frac{m_e}{m_p} \right)^2 0.665 \cdot 10^{-28} \text{ m}^2$$

We have to take into account for the phase lag of the individual electrons w.r.t. each other:

$$\sigma_{ud} = \sum_{i=1}^{N} \sigma_T \cos(kx)$$

$$k = \frac{2\pi}{\lambda_d} \quad x = \left| \vec{x}_1 - \vec{x}_i \right| + \left| \vec{x}_2 - \vec{x}_i \right|$$
Radar scattering
What do we see?

Transmit frequency

V/Hz

10^{-7}  10^{-8}  10^{-9}  10^{-10}  10^{-11}

f(\text{Hz})

1.6e+09  2.4e+09  3.2e+09  4e+09  4.8e+09

Cell phone

Klystron noise