PLASMA AND HIGH-ALTITUDE ELECTROMAGNETIC PULSE PROPAGATION

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***Abstract*:** In this study, we use the Compton scattering to investigate how plasma forms and how this process affects the high-altitude propagation of an electromagnetic pulse (EMP). The prior work's authors conducted this research. When secondary electron-ion couples collide, plasma is created. It is expected that the secondary electrons would move at relativistic rates since the primary gamma rays had energy on the order of a few MeV. Therefore, while studying the impact of relativistic speeds on the propagation of high-altitude electromagnetic pulses, mass fluctuations are taken into account. Our calculations suggest that the emitted field degrades at a slower rate than was suggested by prior research.

Keyword : Electromagnetic Pulse, Plasma, Scattering, HEMP, High Energy, Relativistic Effect

I. INTRODUCTION

The gamma rays from the nuclear explosion climb quickly, in only a few nanoseconds. Compton recoil electrons with energy on the order of 1 MeV are generated by these when they move through air. Secondary electron-ion pairs are created along the path of the Compton electron as well. These secondary electrons, unlike the Compton electron, do not carry a significant electric current during the generation stage, but they do wander when subjected to an electric field. Plasma (Fig. 1) is perhaps created when electrons and ions combine [1].

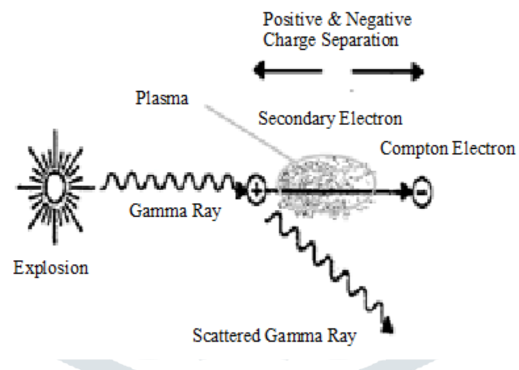

Fig.1. Schematic of generation of Plasma.

The total current density includes primary current density due to Compton electrons and the secondary current density in the plasma. This current is the source of generation of electromagnetic pulse (EMP), where asymmetries of gamma source and surrounding medium density, and geomagnetic field play an important role. Since the gamma radiation produced in the explosion likewise travels at the speed of light, the Compton current pulse also does so at relativistic speed. The EMP, which operates like a bolt of lightning, is significantly affected by the traveling pulse, a feature of the Compton current pulse. Electronic devices that are connected to power sources or antennas may be severely damaged by the EMP [2,3]. Depending on how bad the damage is, it might cause anything from a minor breakdown to a total burnout. Due to the introduction of a delay in the inelastic ground scattering and capture sources, the scenario shifts for an explosion that happens at low altitude. As the burst height increases, the air density decreases, resulting in less intense inelastic scattering and air capture, and a longer gamma ray lifetime. A high altitude above 100 km or so, both the gamma rays and X-rays (generated from photon electron heated materials of the nuclear device) radiated from explosion produce current under burst point. However, X-rays are absorbed quickly, and hence, only the gamma rays are considered under study. Research has been conducted in the pastand plasma has also been taken into account, but the relativistic effects of the secondary electrons have been neglected [2,4]. Therefore, we aim at solving the problem of plasma production and its impact on high altitude EMP propagation under the effect of relativistic speed of secondary electrons.

II. HIGH ALTITUDE ELECTROMAGNETIC PULSE

At altitudes of 100 km or more, the nuclear device's heated materials emit X rays, which in turn produce photoelectrons in the physical model. These photoelectrons are also responsible for the current and light they emit. There are two zones where the gamma and X ray currents generated by HEMP are at their strongest: Even though the air density is likely to be low in this area, gamma ray and X-ray intensity are maximum around the explosion. In the Earth's atmosphere, the region of peak absorption for explosion gamma rays with a mean energy of about one MeV and for explosion X-rays with a Planck distribution corresponding to a nominal temperature of about one keV occurs at altitudes of about 20 to 40 kilometers for gamma rays and of about 70 to 110 kilometers for X-rays, respectively.

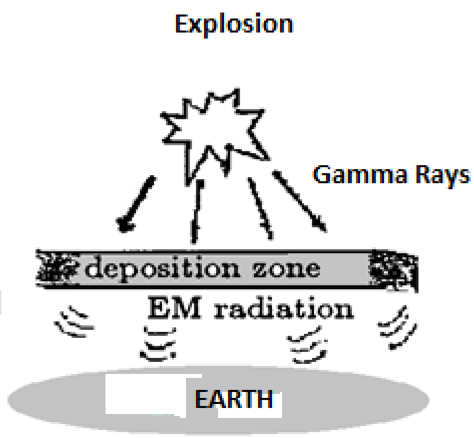

Fig.2. Propagation of electromagnetic pulse.

The fission process produces some of the gamma rays directly, while others are generated indirectly by the inelastic scattering of neutrons in the device material over distances of 100 km or more. Both of those things happen. Compton electrons are emitted when these rays interact with the atmosphere. Compton electrons have so much energy that they can match the speed of light. It's possible that the Compton current has a radial component. On the other hand, the long free path of Compton electrons makes them susceptible to deflection by Earth's magnetic field. To create transverse magnetic field components that are perpendicular to the radial direction, a deflection in the magnetic field generates a Compton current. This results in a radial component, indicated by the symbol Jr, and two transverse components, designated by the symbols J_f and J, in the radiated current. Transverse magnetic (TM) waves are emitted by the components J_r and J, whereas transverse electric (TE) waves are emitted by the component J_f. We adopt spherical coordinates, as shown in Fig. 2, with the origin at the explosion site and the polar axis pointing in the direction of the Earth's magnetic field [5,6]. This is for the purpose of simplicity and clarity.

III. MATHEMATICAL EQUATIONS

An electromagnetic pulse is produced by the high current and high density of electrons in the atmosphere after a nuclear explosion, and this pulse travels at the speed of light, far away from its source. Maxwell's equations for charge density and total current density J are connected in the following way.

$$\nabla \times B = \frac{1}{c}\frac{\partial E}{\partial t} + \frac{4\pi}{c} J, \qquad (1a)$$

$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t}, \qquad (1b)$$

$$\nabla . B = 0, \qquad (1c)$$

$$\nabla . E = 4\pi\rho. \qquad (1d)$$

In this context, we are only concerned with the later kind of pulse. A function, $\zeta = t - r/c$, where r is the distance from the explosion, describes the temporal behavior of the pulse, and it changes fast with delayed time. The slowed down time transition is as follows:

$$\frac{\partial}{\partial t} \to \frac{\partial}{\partial \tau}, \qquad (2a)$$

$$\nabla_t \to \nabla_\tau - \frac{\hat{r}}{c}\frac{\partial}{\partial \tau}, \qquad (2b)$$

where $\hat{r}$ is the unit vector in the direction of source to observer. This transformation modifies the Maxwell's equations to

$$\nabla \times B - \frac{1}{c}\hat{r} \times \frac{\partial B}{\partial \tau} = \frac{1}{c}\frac{\partial E}{\partial \tau} + \frac{4\pi}{c} \qquad (3a)$$

$$\frac{1}{c}\frac{\partial B}{\partial \tau} = -\nabla \times E + \frac{1}{c}\hat{r} \times \frac{\partial E}{\partial \tau} \quad (3b)$$

$$\nabla . B - \frac{1}{c}\frac{\partial B}{\partial \tau} = 0 \quad (3c)$$

$$\nabla . E - \frac{1}{c}\frac{\partial E}{\partial \tau} = 4\,\pi\rho \quad (3d)$$

One can eliminate E from the Maxwell's equations and get equation involving B only or vice - versa. As Karaz and latter [3] showed, the time variation of field from the transverse compoments is more rapid than the spatial components. Hence, the radiating component of E field satisfy

$$\frac{\partial E_r}{\partial \tau} + 4\pi J = 0, \quad (4a)$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rE_\theta) + \frac{2\pi}{c}J_\theta = 0, \quad (4b)$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rE_\phi) + \frac{2\pi}{c}J_\phi = 0. \quad (4c)$$

For the magnetic field, analogous equations are derived. On average, when the Compton electrons proceed in the direction of photon propagation, a huge number of secondary electrons are created. The increased conductivity of the air as a result of this impact has repercussions for the strength of the temporal behavior and the variability of the fields. This is analogous to a quiescent plasma, in which the particles' paths are set only by the strength of the nearby electric field and their interactions with the air. Secondary plasma currents must be accounted for in the current density J together with the original electron currents.

$$J_{total}=J_{primary}+J_{secondary}\,. \quad (5)$$

The dynamics of secondary / plasma electons can be understood based on the equation of their motion $\frac{d(mv)}{dt} = -eE$ through Lorentz model. Here the total time derivative is defined by

$$\frac{d}{dt} = \frac{\partial}{\partial t} + v\frac{\partial}{\partial x}$$

The secondary elecrons may achieve relativistic speeds because the energy released in the explosion is on the order of MeV. The electrons in the produced plasma exhibit relativistic mass variation as a result of their relativistic speed. The equation of motion of electrons in plasma looks like this if we regard relativistic mass variation ($m=\gamma m_0$) and as γ to be its velocity dependent:

$$\frac{\partial}{\partial t}\left(\frac{v}{\sqrt{1-v^2/C^2}}\right) = -\frac{e\boldsymbol{E}}{m_0}$$

The simple calculation gives

$$\frac{dv}{\sqrt[3]{1-v^2/C^2}} = -\frac{eE(t)}{m_0}\,dt$$

On integrating we have

$$\frac{v}{\sqrt{1-v^2/C^2}} = -\frac{e}{m_0}\int E(t)dt$$

For the case when the number n is not a positive integer the binomial expansion for $-1 < \frac{v}{C} < 1$ become

$$v\left(1+\frac{1}{2}\left(\frac{v}{C}\right)^2+\frac{3}{8}\left(\frac{v}{C}\right)^4+\frac{5}{16}\left(\frac{v}{C}\right)^6+\cdots\right) = -\frac{e}{m_0}\int \boldsymbol{E}(t)dt \quad (6)$$

This equation show that velocity of plasma electron is not finite but related by a series equation as given by equation (6a). For non-relativistic variation $\frac{v}{C} \to 0$, series expansion of velocity has only first term i.e.

$$v = -\frac{e}{m_0}\int \boldsymbol{E}(t)dt$$

This is same expression for velocity of plasma particle as calculated by Karzas [8,9] in 1965 and H. J. Longley and C. L. Longmire [7] in 1969.The current $-ev$ due to first term of velocity for a plasma electron created at time t_0 is given by

$$-ev(x,t) = \frac{e^2}{m_0}\int_{t_0}^{t} dt'\, e^{-f(t-t')}\, E(t) \quad (7)$$

= K a constant valve at a fixed time

Due to presence of many terms on left hand side of eq.(6) , reduces secondary current produces by plasma . If we consider upto second term of velocity expansion and neglecting higher order terms we have

$$v\left(1+\frac{1}{2}(\frac{v}{C})^2\right) = -\frac{e}{m_0}\int \boldsymbol{E}(t)dt = K$$

Or $v^3 + 2C^2v - 2C^2K = 0$

This cubic equation has following three solution

$$v = \frac{2\,C^2}{\sqrt[3]{3}\,\sqrt[3]{\sqrt{3}\,\sqrt{8\,C^6+27\,C^4\,K^2}\,-9\,C^2\,K}} - \frac{\sqrt[3]{\sqrt{3}\,\sqrt{8\,C^6+27\,C^4\,K^2}\,-9\,C^2\,K}}{3^{2/3}}$$

$$v_2 = \frac{(1-i\sqrt{3})\sqrt[3]{\sqrt{3}\,\sqrt{8\,C^6+27\,C^4\,K^2}\,-9\,C^2\,K}}{2\times 3^{2/3}} - \frac{(1+i\sqrt{3})\,C^2}{\sqrt[3]{3}\,\sqrt[3]{\sqrt{3}\,\sqrt{8\,C^6+27\,C^4\,K^2}\,-9\,C^2\,K}}$$

And

$$v_3 = \frac{(1+i\sqrt{3})\sqrt[3]{\sqrt{3}\,\sqrt{8\,C^6+27\,C^4\,K^2}\,-9\,C^2\,K}}{2\times 3^{2/3}} - \frac{(1-i\sqrt{3})\,C^2}{\sqrt[3]{3}\,\sqrt[3]{\sqrt{3}\,\sqrt{8\,C^6+27\,C^4\,K^2}\,-9\,C^2\,K}}$$

Being v_2 and v_3 velocity component are complex conjugate and imageniory quantity so can be neglected.

The plasma electrons are created and disappeared simulatenously. So the $\dot{n}(t_0)$ is rate of creation and n(t) being net plasma electron density. Then the final expression for plasma electron contribution to current density is

$$J_{secondary}(t) = \frac{e^2}{m_0}\int_{\infty}^{t} dt'\, e^{-f(t-t')}\, E(r,t)n(r,t) - J_1 \qquad (8)$$

Here J_1 is correction term that is arising due to velocity series expansion and due to this contribution secondary current density will be less as computed by Karzas [8,9] in 1965 and H. J. Longley and C. L. Longmire [7]. If we include this contribution to the field equations, we obtain

$$\frac{\partial}{\partial r}[eE_\theta(r,\tau)] + \frac{2\pi}{c}\frac{e^2}{\gamma m}\int_{-\infty}^{\tau} d\tau' r E_\theta(r,\tau')n(r,\tau')e^{-f(r)(\tau-\tau')} + \frac{2\pi}{c}\, r\, J_\theta(r,\tau) = 0 \qquad (9)$$

$$\frac{\partial}{\partial r}[eE_\phi(r,\tau)] + \frac{2\pi}{c}\frac{e^2}{\gamma m}\int_{-\infty}^{\tau} d\tau' r E_\phi(r,\tau')n(r,\tau')e^{-f(r)(\tau-\tau')} + \frac{2\pi}{c}\, r\, J_\phi(r,\tau) = 0 \qquad (10)$$

Similar types of equations are obtained for B_θ and B_ϕ. These equations are not easy to solve because of spatial variation of f(r,τ) in the exponential term. However if f(r,τ) is large compared to the frequencies in E and n_o, under this assumption, we get

$$\frac{\partial}{\partial r}(e\,F) + \frac{2\pi}{c}\frac{e^2}{\gamma m}\, n(r,t) r\, F + \frac{2\pi}{c}\, r\, J = 0 \qquad (11)$$

Here F is a general field.So the above equation is for both the electrical field components E_θ & E_ϕ, and magenetic field components B_θ & B_ϕ, and also for the current densities J_θ and J_ϕ. The general solution of equation (11) for E(r,τ) can be written as

$$E(r,\tau) = -\frac{2\pi}{c}\frac{1}{r}\int_0^r dr' r'\, j\,(r',\tau)e^{-\frac{2\pi e^2}{\gamma mc}\int_{r'}^{r} n(r,t)dr'} \qquad (12)$$

IV. RESULTS AND CONCLUSIONS

Under the influence of mass fluctuation of the secondary electrons owing to their relativistic speeds, we have computed the transverse field component from a pulse of HEMP. This occurred because of the tremendous energy and relativistic speeds of the fundamental particles. Our investigation has revealed an additional term in the exponential terms; we have denoted this as 1/ γ. In contrast to what has been seen by other researchers, the field is predicted to decay at a slower pace thanks to the factor γ appearing in the exponential terms that we have calculated. In addition, we discovered that the current total is still below what was expected by other employees. This was because it takes more effort to get the secondary electrons moving at relativistic speeds, therefore energy was being wasted.

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