Asymmetric Backward Peaking Bremsstrahlung Radiation Pattern from a Relativistic Particle Accelerated by Lightning Leader Tip Electric Field

EGU General Assembly 2020

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01/05/2020

Introduction

- When Terrestrial Gamma-Ray Flashes (TGFs) were first observed by detectors of the Compton Gamma Ray Observatory (CGRO) (Fishman et al. 1994), their association with Bremsstrahlung was shown with the observation of slopes in ionising radiation indicating continuous electromagnetic spectrum (Joseph R. Dwyer, Smith, and Cummer 2012) and supported by Monte Carlo simulations that included Bremsstrahlung process (J. R. Dwyer 2007).
- The Poynting vector of the emitted radiation, i.e., the radiation pattern around a single particle under the external lightning leader tip electric field during its interaction with other particles or atoms is not quite well known.

Theory Structure

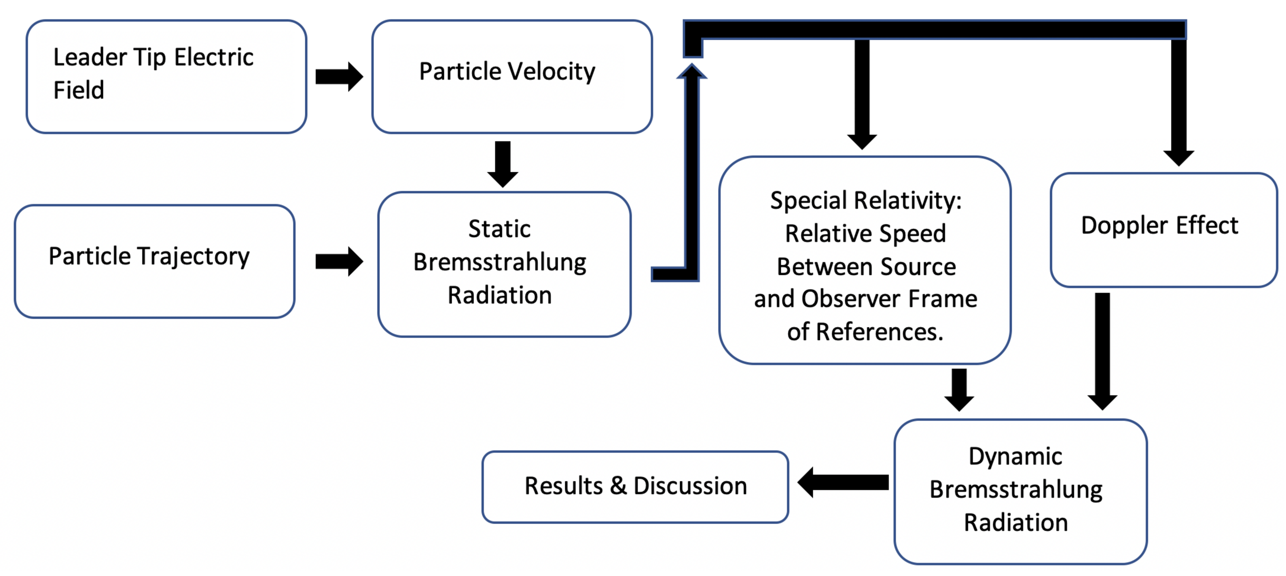

Figure 1 – Flow Chart of Theory Structure

$$\frac{d^2I}{d\omega\Omega_{rad}} = \frac{z^2e^2(\gamma\omega(1-\beta S_{SpecialR}cos(\theta_{n,\beta}))^2}{4\pi^2c\epsilon_0}\Bigg| sin(\theta_{n,\beta}) \Bigg[-\frac{s_{fv}s_fz(s_{ft})^{1.461}4.365\times10^{26}}{c}\Big[\pi^{1/2}2^{-(1/2)v}\alpha^{-v-1}e^{-\frac{y^2\alpha^{-2}}{8}}\times D_v(2^{-1/2}\alpha^{-1}y)\Big] + \frac{s_{fv}zs_f(s_{ft})^{1.5}1.565\times10^{27}}{c}\Big[\pi^{1/2}2^{-(1/2)v}\alpha^{-v-1}e^{-\frac{y^2\alpha^{-2}}{8}}\times D_v(2^{-1/2}\alpha^{-1}y)\Big]\Bigg]\Bigg|^2 \tag{1}$$

Where,

$$\alpha^2 = \frac{b^R(\gamma\omega(1-\beta S_{SpecialR}cos(\theta_{n,\beta}))^R(sin(\theta_{n,\beta}))^R}{(\tau^R)^2c^R}\ [s^{-2}]$$

$$y = \frac{\gamma\omega(1-\beta S_{SpecialR}cos(\theta_{n,\beta})sin(\theta_{n,\beta})a}{c\tau}\ [s^{-1}]$$

Equation (1), describes radiation intensity $[Js^{-1}]$ per emitted angular wave frequency $[rads^{-1}]$ per Solid angle $[rad]$. Solid angle helps describe and plot the radiation intensity around a single particle. Hence, plot of radiation intensities around a single particle gives us information about the shape of emitted radiation with location of maximum and minimum intensities and how it varies as particle gains up speed and changes it's trajectory. In addition, R describes the magnitude of the novel Bremsstrahlung asymmetry, $S_{SpecialR}$ dimensionless quantity describing ralative velocity between the observer and the single particle. $S_{SpecialR}=1$ meaning observer is in laboratory frame of reference and particle speed is β. $S_{SpecialR}=0$ meaning observer is in the particle's frame of reference. Hence, $\beta=0$ and observer would see a dipole radiation pattern.
Formula explaining the radiation patterns should also be able to explain how particle attains relativistic forward and backward peaking lobes from initial non-relativistic dipole radiation pattern as particle's velocity increases.

Results

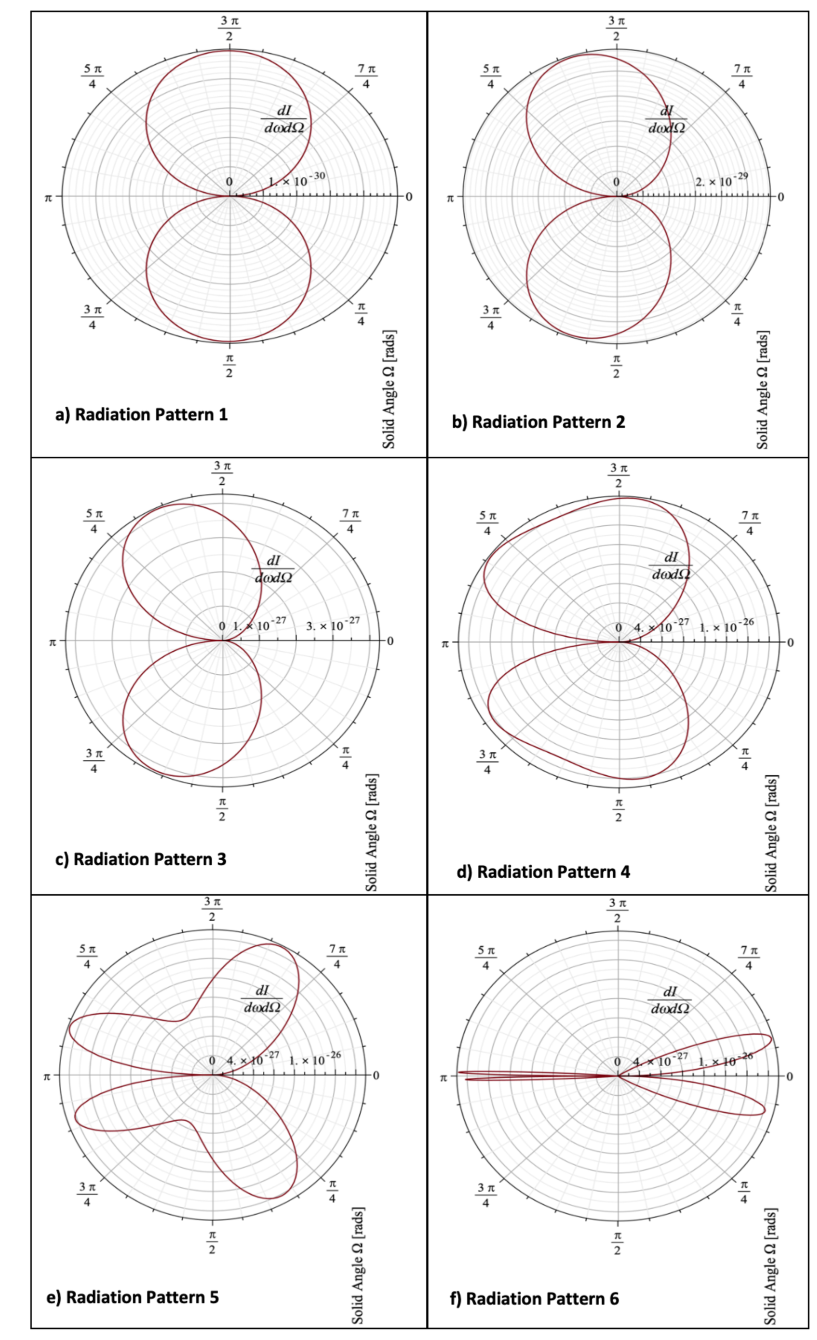

Figure 2 – Radiation Patterns Emitted By Anti-Clockwise Rotating Charged Particle. Particle's forward direction is to the right - towards 0 $rads$ in 8 radiation plot.

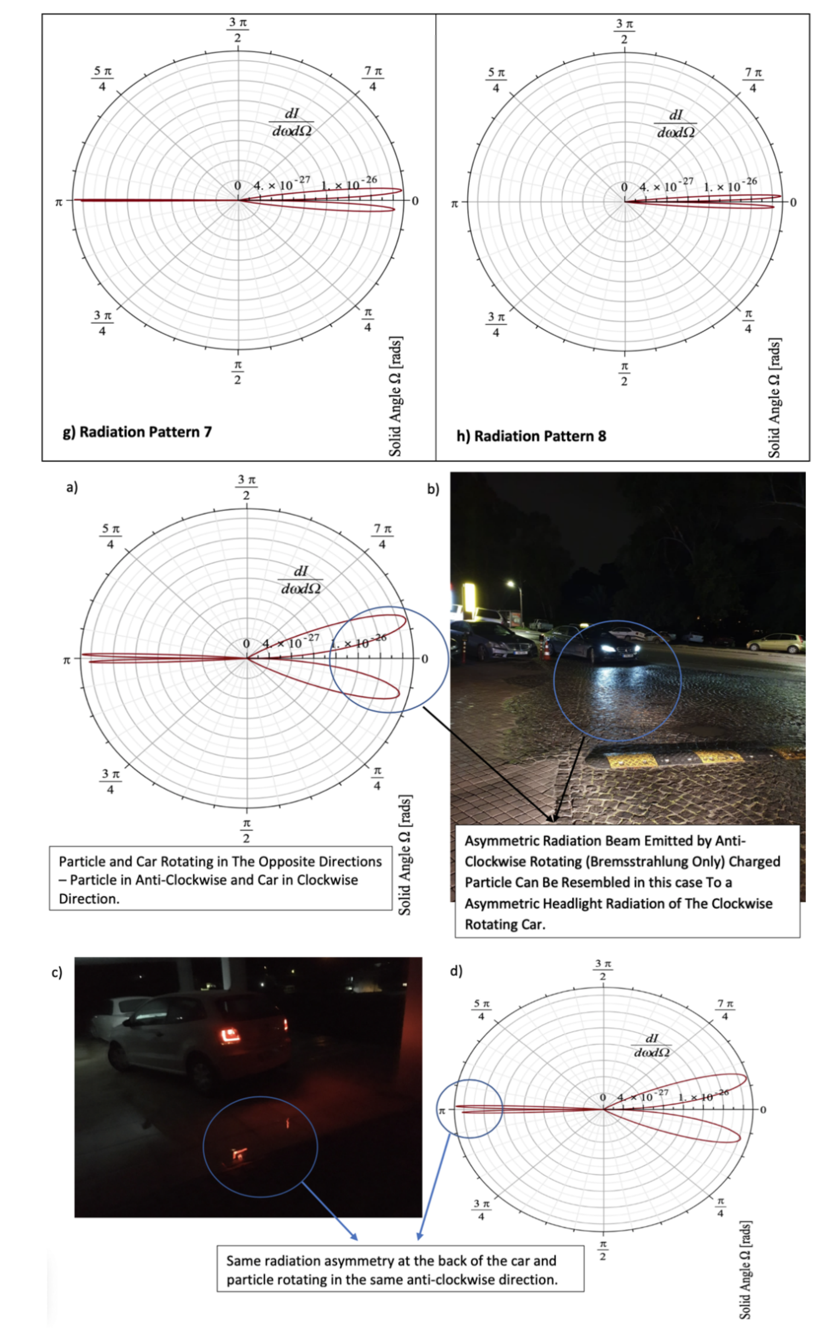

Figure 3 – Radiation Patterns Emitted By Anti-Clockwise Rotating Charged Particle.

Table of Input Velocity Presented as Ratio to Speed of Light β and Emitted Radiation Frequency (Hz)		
Pattern Name	β (Dimensionless)	Emitted Radiation Frequency (Hz)
Pattern 1	0.02	1 k
Pattern 2	0.36	10 k
Pattern 3	0.67	1 M
Pattern 4	0.69	7 M
Pattern 5	0.77	10 M
Pattern 6	0.85	100 M
Pattern 7	0.87	500 M
Pattern 8	0.90	1 G

Table 1 – Input Parameters, velocity as a ratio to speed of light β and emitted radiation frequency by the particle for 8 different radiation patterns. Emitted radiation frequency by the single particle is an input parameter to the final equation (1). It plays a crucial role in delivering an important information about the shape of radiation and determining particle's total acceleration, hence the total velocity indirectly.

Transition from Dipole radiation pattern to forward and backward peaking radiation pattern is demonstrated in radiation pattern 4 and 5 where dipole collapses to form four maxima. Radiation patterns on polar plot has to start from 2π $rads$ until 0 $rads$ for a complete radiation around particle. This is because particle starts from retarded time and radiates until chronological time t=0 s as shown in figure 5 and 6.

Constructed Theoretical Concept of Nature and Observations

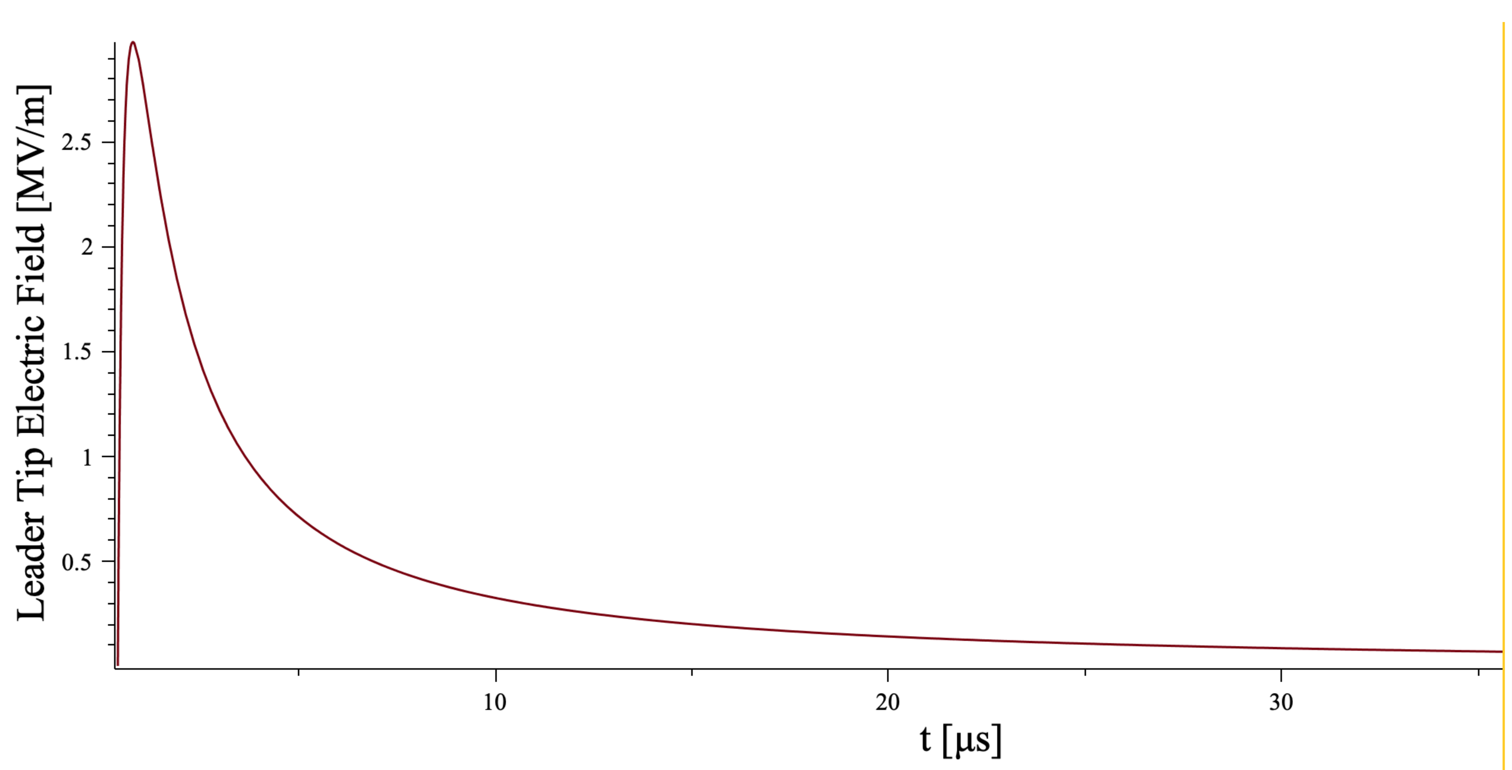

Figure 4 – Graph of Modelled Lightning Leader Tip Electric Field. Lightning leader tip electric field was mathematically modelled to fit observed electric field characteristic of lightning discharges. Lightning discharges display sharp rise and slow decaying electric field characteristics. Peak value of leader tip electric field was chosen to be ~ 3 MV/m as it is the approximate conventional electrical breakdown of air. In order for RREA (Relativistic Runaway Electron Avalanche) mechanism to develop, electrons to reach relativistic speeds and Bremsstrahlung process to occur, leader tip electric field must be in the order of ~ 26 MV/m at 101 kPa of atmospheric pressure (Babich et al. 2015).

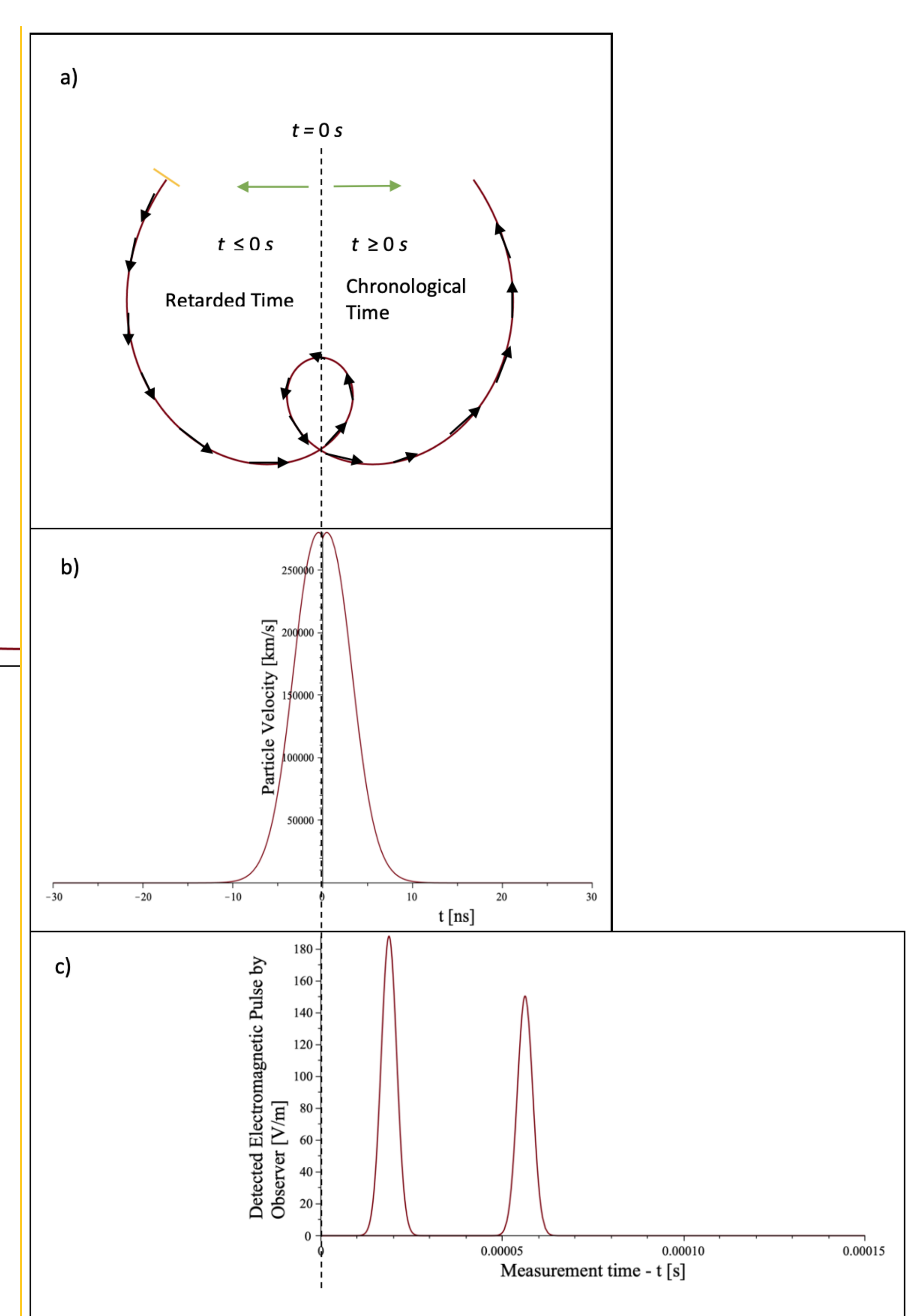

Figure 5 – Theory of Practical Observations

a) Particle's starting position is indicated with a yellow line and starts accelerating from -10 ns until $t=0$ s as a result of external leader tip electric field and Coulomb electric field (Bremsstrahlung) of target particle in atmosphere.
b) Shows how particle's velocity changes as a function of time. Particle is still allowed to propagate to positive time values, however, the starting time is from negative time values (Retarded Time). Negative time is required to reflect the reality that when signal is measured by observer at $t=0$ s, it has to travel some time from source to observer and also physical process that causes Bremsstrahlung emission requires some time to take place. All of these physical processes are not observed by observer in chronological time, hence it occurs in negative retarded time.
c) Sketches when the observer would receive the emitted Bremsstrahlung signal. It is plotted using Dirac Delta function and does not reflect the actual timing. First signal could also be received at $t=0$ s, however not in retarded time as it would than contradict the observations where there is no negative time.

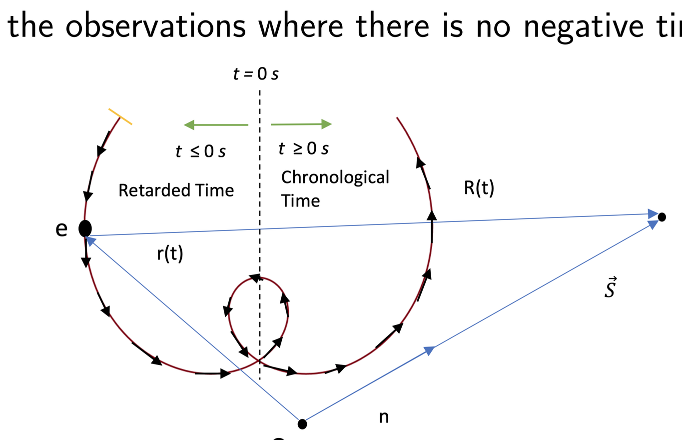

Figure 6 – Radiation Emission By change in Velocity over Time by A Coulomb Force of Other Charges and External Leader Tip Electric Field. O represents the target particle that defines the spiral trajectory of electron due to Coulomb force. Particle (electron) acceleration and velocity vectors are displayed with black arrows and are tangential to the spiral trajectory (red line). Hence, perpendicular to the position vector $r(t)[m]$. $R(t)[s]$ gives the distance between accelerated single particle (source) and the observer all the time. P is the position of observer. $\vec{S}[W/m^2]$ is a Poynting vector of emitted electromagnetic wave and it gives the direction of energy flow rate per area. n (Dimensionless) unit vector in the direction of power flow.

Conclusions

- Radiation pattern was found to be peaking in backward direction (Low frequency) as well as already known forward direction (High frequency).
- Doppler effect causes peaking lobes of radiation in forward and backward direction to be asymmetric about an axis perpendicular to the velocity vector of the particle.
- Novel asymmetry of peaking lobes with respect to particles velocity vector was found to be unique to Bremsstrahlung due to particle following curved trajectory.

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Research Funding Institutions

Funding organisations supporting the research of this work and participating in Annual EGU General Assembly 2020:

Met Office

EPSRC Engineering and Physical Sciences Research Council