

Bremsstrahlung Electron Crossing Different Mediums: Extension of Asymmetric Backward Peaking Radiation Pattern from a Relativistic Particle Accelerated by Lightning Leader Tip Electric Field

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Key Points:

- Bremsstrahlung asymmetry, R causes Bremsstrahlung angle, θ_{brem} between two forward and backward peaking lobe pairs to get either larger or smaller as the radiation crosses different mediums
- More mediums the bremsstrahlung electron crosses, forward-backward peaking radiation pattern tends to either asymmetric, distorted Dipole radiation pattern or asymmetrically oriented forward backward peaking radiation pattern.
- Asymmetrically oriented forward backward peaking radiation pattern means each four lobe would have different angle from the particle's velocity vector. For bremsstrahlung in vacuum, all four lobes had same angle from the particle's velocity vector, which was half of the bremsstrahlung angle, $\frac{\theta_{brem}}{2}$ when particle was in vacuum. Bremsstrahlung particle crossing different mediums have each of its peaking lobe at different angle from the velocity vector where each is $\Omega_1, \Omega_2, \Omega_3, \Omega_4$
- Bremsstrahlung asymmetry, R causes a difference in top and bottom forward peaking lobes which in turn causes different magnitudes of diffraction
- Doppler effect causes different diffraction between forward and backward peaking lobes. Backward peaking lobes diffract more compared to forward peaking lobes
- Novel formula extended Snell's Law to diffraction of bremsstrahlung asymmetric, R waves and predicting final direction of the forward and backward lobe pairs
- As the bremsstrahlung electron follows spiral curved trajectory, in theory, all peaking lobes enter new medium at different angles. Hence, all diffract at different magnitudes. This is another reason that contributes to the increase and decrease in Bremsstrahlung angle, θ_{brem} between forward-backward peaking lobes

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Abstract

Previously the radiation patterns of combined parallel and perpendicular motions from the accelerated relativistic particle at low and high frequencies of the bremsstrahlung process with an external lightning electric field were explained. The primary outcome was that radiation patterns have four relative maxima with two forward peaking and two backward peaking lobes. The asymmetry of the radiation pattern, i.e., the different intensities of forwarding and backward peaking lobes, is caused by the Doppler effect. A novel outcome is that bremsstrahlung has an asymmetry of the four maxima around the velocity vector caused by the curvature of the particle's trajectory as it emits radiation. Previously stated bremsstrahlung asymmetry, R was an asymmetry in the radiation lobe pairs about particles velocity vector. Bremsstrahlung asymmetry used to occur at the same level in both forward radiation lobe pairs and backward radiation lobe pairs. However, in high-density mediums where the emitted wave can lag behind the speed of the particle, symmetry of the magnitude of bremsstrahlung asymmetry, R differs between forward peaking radiation lobe pairs relative to backward peaking radiation lobe pairs. This is another novel asymmetry and it causes bremsstrahlung asymmetry, R to be larger in the forward peaking compared to backward peaking radiation. The outcome is the shrink in radiation length that occurs in the backward peaking lobes. This extended work reports, changes in the radiation pattern as the emitted wave propagates through different mediums. Two novel formulas are derived from Snell's law for a particle entering the medium horizontally and from any other angle between $\Pi/2$ and $-\Pi/2$ radians. The novel outcome is the change in angle between forward peaking radiation lobe pair and backward peaking radiation lobe pair defined as bremsstrahlung angle, θ_{brem} . When the bremsstrahlung particle crosses different mediums, change in angle between the forward and backward radiation lobe pairs, bremsstrahlung angle, θ_{brem} breaks into its components as each lobe changes angle at different magnitudes from the particle's velocity vector. Therefore, bremsstrahlung angle, θ_{brem} between forward-backward peaking lobes transforms into individual angles $\Omega_1, \Omega_2, \Omega_3, \Omega_4$ all measuring from the particle's velocity vector.

1 Introduction

Bremsstrahlung radiation patterns were predicted to be forward and backward peaking with associated novel bremsstrahlung asymmetry, R (Yücemöz & Füllekrug, 2021). In addition, the time evolution of dipole radiation pattern into forward-backward peaking was demonstrated. The reasoning for the existence of forward-backward peaking due to the collapse and separation of the lobes of the dipole radiation pattern was associated with the conservation of symmetry axes (Yücemöz & Füllekrug, 2021). Furthermore, the bremsstrahlung process of high-density mediums revealed a new outcome that symmetry of the bremsstrahlung asymmetry, R about the axis perpendicular to the direction of particle's motion, between the forward and backward peaking side is broken. Increasing refractive index causes bremsstrahlung asymmetry, R to exist at different ratios between forward and backward peaking radiation lobe pairs. Increasing refractive index increases the difference in bremsstrahlung asymmetry between the front radiation lobe pairs compared to backward radiation lobe pairs. Furthermore, increasing the refractive index shortens the radiation length in the backward peaking radiation side. This extended modelling predicts the changes in the emitted radiation pattern as the accelerating particle transits to different mediums. Novel equations 12 and 13 extended from Snell's law combining previous knowledge of the bremsstrahlung asymmetry parameter, R predicts how the symmetric bremsstrahlung angle, θ_{brem} between forward and backward peaking lobe pairs and how symmetric half bremsstrahlung angle, $\frac{\theta_{brem}}{2}$ from the particle's velocity vector within each lobe pair breaks. Novel symmetry break of bremsstrahlung angle, θ_{brem} into individual angles $\Omega_1, \Omega_2, \Omega_3, \Omega_4$, all describing the angle for each radiation lobe from particle's velocity vector. This novel symmetry break causes the ra-

83 diation pattern to be a distorted combination of both either forward or backward peak-
 84 ing radiation pattern and the distorted dipole radiation pattern.

85 1.1 Aims & Objectives

86 This theoretical approach aims to extend the previous bremsstrahlung model to
 87 different mediums. Previously, the bremsstrahlung electron was propagating inside a vac-
 88 uum. This report puts bremsstrahlung electron into crossing different mediums and math-
 89 ematically models changes in the radiation pattern as a result of wave refraction by ex-
 90 tending Snell's law for the waves that have larger wavelengths than the particles present
 91 in that specific medium. Therefore, mediums where wave refraction dominates wave scat-
 92 tering.

93 2 Equation Relating Top and Bottom Radiation lobes Together Us- 94 ing Bremsstrahlung Asymmetry, R

95 Considering forward peaking part of the overall radiation pattern. Radiation in-
 96 tensity, I of top lobe (I_T) can be related to the bottom lobe (I_B) with bremsstrahlung
 97 asymmetry, R mathematically by

$$I_T = \frac{I_B}{(1 - R)} \quad (1)$$

98 This information can be used to find the bremsstrahlung angle, θ_{Brem} between the
 99 two forward peaking radiation lobes that are bremsstrahlung asymmetric, with asym-
 100 metry value R.

101 By knowing the radiation length difference or in other terms, linear distance in the
 102 form of radiation intensity, $\Xi [Js^{-1}]$ between the maximum points of two radiation in-
 103 tensities, I in the forward peaking lobes, bremsstrahlung angle between the two forward
 104 peaking lobes can be written as,

$$\cos(\theta_{Brem}) = \frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B} \quad (2)$$

105 The equation 1 and 2 can also be used for backward peaking radiation lobes.

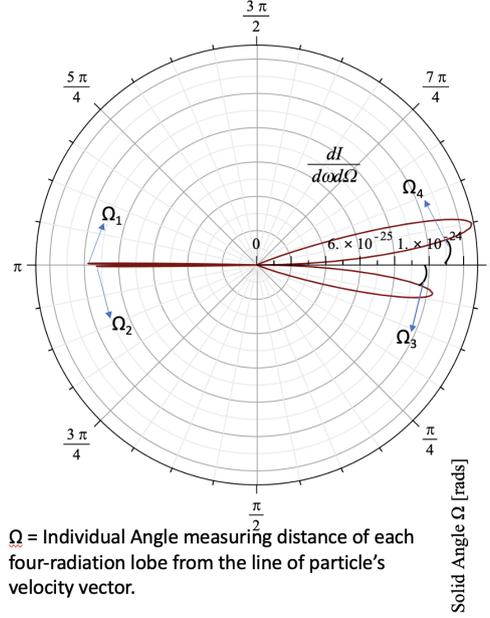


Figure 1. The Radiation patterns are emitted by the anti-clockwise rotating charged particle - bremsstrahlung process. High density (particle travelling inside the water) medium causes a novel asymmetry about a line perpendicular to the direction of motion of a particle. This novel asymmetry causes bremsstrahlung asymmetry, R to occur at different proportions in forward and backward peaking lobe pairs. Therefore, bremsstrahlung asymmetry, R is higher in forward peaking radiation and lower in backward peaking radiation. Moreover, a high-density medium also causes radiation length to shorten in backward peaking radiation. Plot is in Polar co-ordinates. Horizontal axis gives the radiation intensity per Solid angle, Ω , per emitted angular radiation frequency, ω . In addition, angle of the Polar plot is the Solid angle, Ω . The values used for plotting are: mean free time $\tau = 30 \mu\text{s}$, number of charges $z = 1$, $a = 100 \mu\text{m}$, $b = 1 \text{ nm}$ (a and b are related to mean free path), $s_{ft} = 1$, $s_f = 1$, $S_{SpecialR} = 1$, velocity-time scaling factor $s_{ftv} = 1 \times 10^9$ and velocity scaling factor $s_{fv} = 8.19 \times 10^{-11}$. Finally, the bremsstrahlung asymmetry is $R = 1/8$. In addition, $\frac{1}{9} \leq R \leq \frac{1}{3}$, medium conductivity, $\sigma = 0.005$, relative permeability, $\mu_r = 0.99$

3 Application of Snell's Law on Bremsstrahlung Asymmetric Radiation Passing Through a Medium with Positive Refractive Index

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3.1 Two different Case Studies

3.1.1 Horizontal Incoming Particle

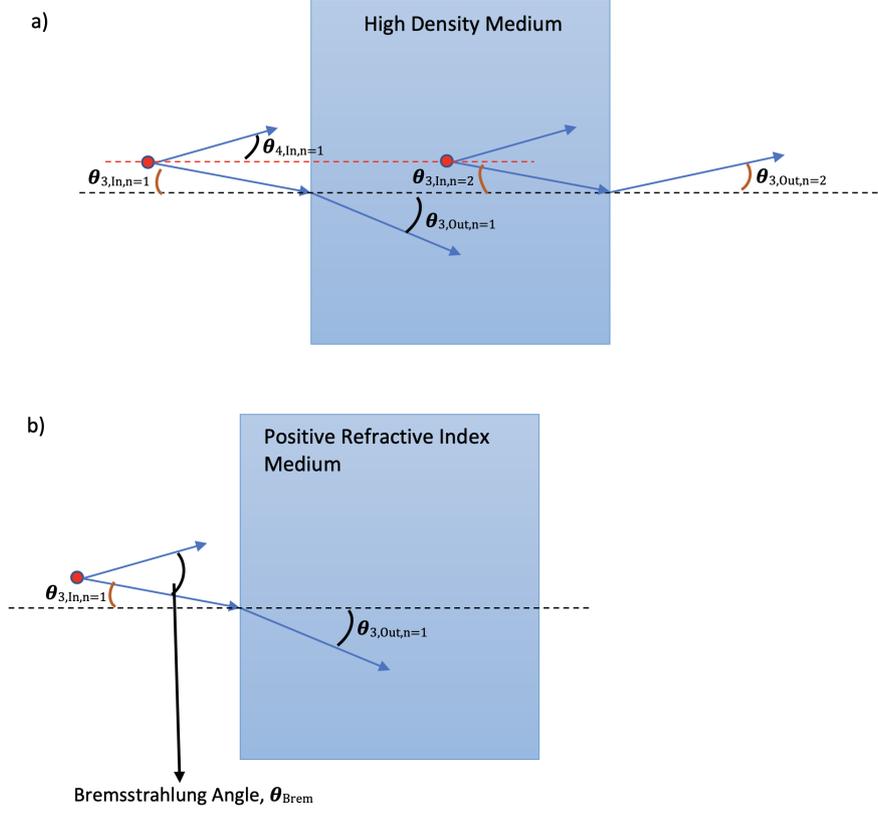


Figure 2. Case study A: the medium is high density such that the bremsstrahlung electron catches its own radiation and continues to emit radiation in the same medium. In this case, the bremsstrahlung electron could gain energy from its own radiation due to a curved trajectory that increases the likelihood of interaction with its own radiation. Case study B: the medium is not high density, the particle still lags its own emitted electromagnetic wave speed. In both cases bremsstrahlung angle, θ_{brem} between two forward peaking lobes increases. This is because of the bremsstrahlung asymmetry, R which changes the radiation intensity, I . Hence, causing a frequency difference between two forward peaking lobes which in turn causes the low-frequency wave to diffract more than the high-frequency lobe. More importantly, as the bremsstrahlung electron crosses more different mediums, the bremsstrahlung angle, θ_{brem} continues to grow such that eventually, the whole radiation pattern can transform back to a dipole radiation pattern. Extremely high frequencies such as X-rays diffract only by a tiny angle. However, forward peaking radiation patterns can start as early as in the MHz frequency range and peak in forward direction as the frequency increases.

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When accelerated relativistic bremsstrahlung electron with bremsstrahlung asymmetric "R" forward-backward peaking radiation pattern enters into a medium with a refractive index of η_2 from a medium with refractive index η_1 , the final direction of the emit-

113 ted radiation in the final medium of η_2 can be predicted using Snell's law in combina-
 114 tion with bremsstrahlung asymmetry, R.

$$\sin(\Omega_{4,Out,n=1}) = \frac{\sin(\Omega_{4,In,n=1})\eta_1}{\eta_2} \quad (3)$$

$$\sin(\Omega_{3,Out,n=1}) = \frac{\sin(\Omega_{3,In,n=1})\eta_1}{\eta_2} \quad (4)$$

115 Introducing the bremsstrahlung asymmetry, R parameter into equations 3 and 4.

116 From equation 1, angle between two forward peaking lobes can be written as,

$$\Omega_{4,In,n=1} + \Omega_{3,In,n=1} = \theta_{Brem} = \cos^{-1} \left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B} \right] \quad (5)$$

117 Hence,

$$\sin(\Omega_{4,Out,n=1}) = \frac{\sin \left(\cos^{-1} \left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B} \right] - \Omega_{3,In,n=1} \right) \eta_1}{\eta_2} \quad (6)$$

$$\sin(\Omega_{3,Out,n=1}) = \frac{\sin \left(\cos^{-1} \left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B} \right] - \Omega_{4,In,n=1} \right) \eta_1}{\eta_2} \quad (7)$$

118 As the emitted radiation could go through many different mediums until it is de-
 119 tected by the detectors, to find the final direction of the emitted radiation through all
 120 of its journey from source particle to receivers, equations 6 and 7 can be written in the
 121 form of series. For the detection after the " n^{th} " medium refractive index

$$\sin(\Omega_{TopLobeakaNo.4,Out,nth}) = \sum_{n=1}^{\infty} \frac{\sin \left(\cos^{-1} \left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B} \right] - \Omega_{Top,In,1+n} \right) \eta_n}{\eta_{1+n}} \quad (8)$$

$$\sin(\Omega_{BottomLobeakaNo.3,Out,nth}) = \sum_{n=1}^{\infty} \frac{\sin \left(\cos^{-1} \left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B} \right] - \Omega_{Bottom,In,n} \right) \eta_n}{\eta_{1+n}} \quad (9)$$

3.1.2 Incoming Particle at an Angle

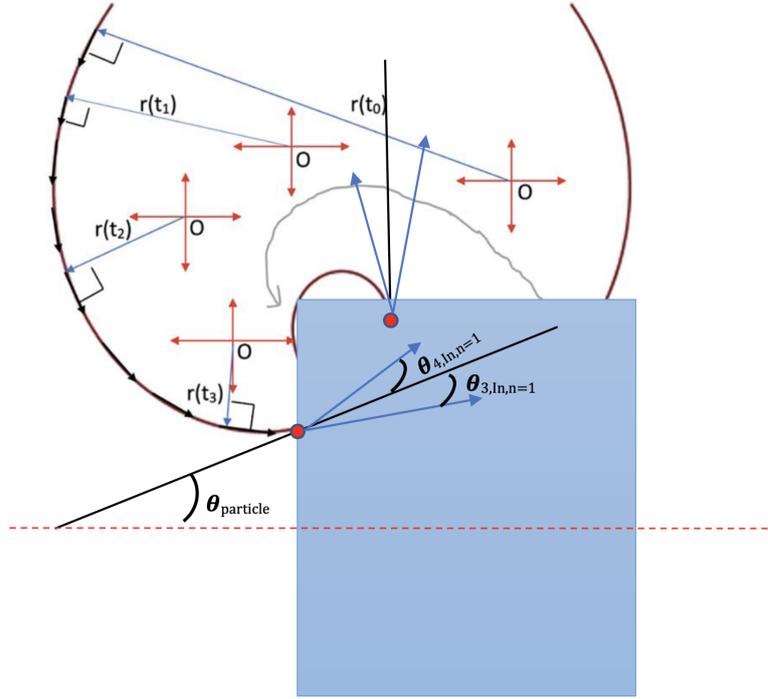


Figure 3. Accelerating bremsstrahlung electron following curved spiral trajectory transiting into a new medium coloured in blue. Orientation of the bremsstrahlung electron from the normal line (Horizontal line) of the new medium is described by the angle $\theta_{particle}$. When radiation is first emitted from the bremsstrahlung particle, each forward peaking lobe in the pair is symmetric about the particle's velocity vector, hence each forward lobe has an equal distance away from the particle's velocity vector. Hence, $\Omega_{3,ln,n=1} = \frac{\theta_{Brem}}{2}$ and $\Omega_{4,ln,n=1} = \frac{\theta_{Brem}}{2}$ from the particle's tangent velocity vector. Therefore, once the $\theta_{particle}$ is known, $\Omega_{3,ln,n=1}$ and $\Omega_{4,ln,n=1}$ are just $\mp \frac{\theta_{Brem}}{2}$ away from the $\theta_{particle}$. This symmetry of the angle of each lobe from the particle's velocity vector is broken once the radiation crosses from one medium into another. This is because of asymmetric refraction that occurs due to asymmetric radiation intensity caused by the bremsstrahlung asymmetry, R , and the curved trajectory.

Slope of the line tangent to the particle's spiral trajectory given by

$$\frac{dy}{dx} = \frac{r(t)' \cos(t) + r(t)'' \sin(t)}{-r(t)' \sin(t) + r(t)'' \cos(t)} \quad (10)$$

Angle, $\theta_{particle}$ of an incident electron into a medium with respect to the horizontal line is,

$$\theta_{particle} = \arctan\left(\frac{r(t)' \sin(t)}{r(t)' \cos(t)}\right) \quad (11)$$

$r(t)'$ is particle's velocity vector and is given by, $\frac{dr}{dt} = \frac{b^R(\omega')^R \cos(\theta_{n,r(t)})^R c}{c^R \omega' \cos(\theta_{n,r(t)})}$

$$\left(\frac{\tau^{2R} \left[t^{2R} \frac{2R}{t} + t^{2R} 2R' \ln(t) \right] - t^{2R} \left[\tau^{2R} \frac{2R}{\tau} + \tau^{2R} 2R' \ln(\tau) \right]}{\tau^{4R}} \right) - \frac{a\tau - at\tau'}{\tau^2} \quad (\text{Yücemöz \& Füllekrug, 2021, Eq. 3})$$

The bremsstrahlung particle, hence the emitted radiation enters different mediums at different angles following a spiral trajectory, bremsstrahlung asymmetry, R and Doppler effect cause differences in frequency for each radiation lobe. Therefore, Each radiation lobe would have distinctive incoming $\Omega_{In,n=1}$ and exit $\Omega_{Out,n=1}$ angles. Incoming angles are given formulated in equations 12, 13, 14, and 15. For backward peaking waves, incoming angles to the different mediums are given in equations 14 and 15. In addition, the forward peaking radiation lobe with angle number 4 has the same entry angle as the backward peaking radiation lobe with angle number two. However, the radiation of angle number four and angle number two propagates in the opposite direction to each other. Similar is also true for the forward peaking radiation lobe with angle number three and backward peaking radiation angle number one. All these peaking radiation lobes with associated angle numbers are shown in Figure 4.

$$\Omega_{4,In,n=1} = \theta_{particle} + \frac{\theta_{Brem}}{2} = \arctan\left(\frac{r(t)' \sin(t)}{r(t)' \cos(t)}\right) + \frac{\cos^{-1}\left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B}\right]}{2} \quad (12)$$

$$\Omega_{3,In,n=1} = \theta_{particle} - \frac{\theta_{Brem}}{2} = \arctan\left(\frac{r(t)' \sin(t)}{r(t)' \cos(t)}\right) - \frac{\cos^{-1}\left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B}\right]}{2} \quad (13)$$

Bringing back the backward peaking radiation pattern,

$$\Omega_{2,In,n=1} = \Omega_{4,In,n=1} \quad (14)$$

and

$$\Omega_{1,In,n=1} = \Omega_{3,In,n=1} \quad (15)$$

142 At the point of the boundary of the medium transition region, the bremsstrahlung
 143 angle, θ_{brem} changes exactly the opposite but at the same rate and magnitude between
 144 pairs. Hence, if the bremsstrahlung angle, θ_{brem} increases between the forward peaking
 145 pairs it would decrease between backward pairs as the radiation crosses between the same
 146 mediums but in the opposite order (i.e one from Medium A to B other from medium B
 147 to A).

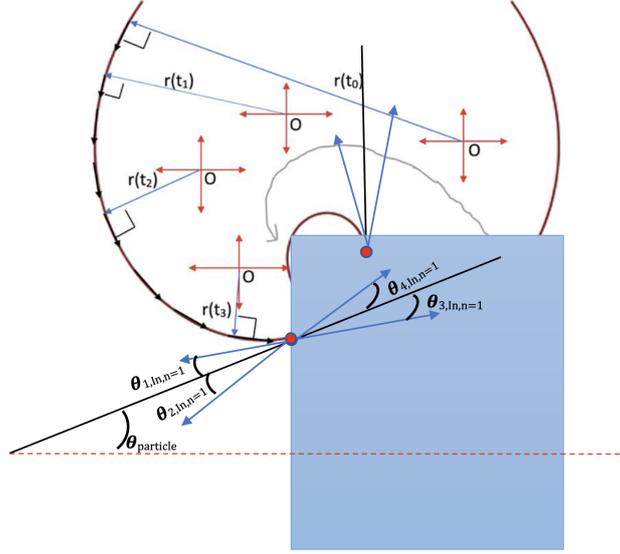


Figure 4. In addition to the Information presented in figure 3, This figure brings back the backward peaking radiation pattern into the equation. As can be seen, backward peaking radiation lobes propagate in the exact opposite directions compared to the forward peaking radiation lobes when radiation is first emitted from the particle. Backward peaking lobes have lower radiation intensity, hence, lower frequency and higher wavelengths due to the Doppler effect. This causes backward peaking radiation lobes to refract less than forward peaking radiation lobes. Which introduces another asymmetry about the line perpendicular to the particle's velocity vector and distortion in the overall radiation pattern.

148 By substituting equations 12, 13, 14 and 15 into equations 3 and 4, final exit an-
 149 gle can now be written for the forward peaking as follows

$$\sin(\Omega_{4,Out,n=1}) = \frac{\sin\left(\arctan\left(\frac{r(t)'}{r(t)'}\frac{\sin(t)}{\cos(t)}\right) + \frac{\cos^{-1}\left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B}\right]}{2}\right)\eta_1}{\eta_2} \quad (16)$$

$$\sin(\Omega_{3,Out,n=1}) = \frac{\sin\left(\arctan\left(\frac{r(t)'}{r(t)'}\frac{\sin(t)}{\cos(t)}\right) - \frac{\cos^{-1}\left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B}\right]}{2}\right)\eta_1}{\eta_2} \quad (17)$$

150 and exit angle for the backward peaking radiation lobes as follows

$$\sin(\Omega_{2,Out,n=1}) = \frac{\sin\left(\arctan\left(\frac{r(t)'\sin(t)}{r(t)'\cos(t)}\right) + \frac{\cos^{-1}\left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B}\right]}{2}\right)\eta_2}{\eta_1} \quad (18)$$

$$\sin(\Omega_{1,Out,n=1}) = \frac{\sin\left(\arctan\left(\frac{r(t)'\sin(t)}{r(t)'\cos(t)}\right) - \frac{\cos^{-1}\left[\frac{I_T^2 + I_B^2 - \Xi^2}{2I_T I_B}\right]}{2}\right)\eta_2}{\eta_1} \quad (19)$$

151 The Refractive index for the refraction of backward peaking radiation is inverted
 152 as the radiation propagates in opposite direction and out of every new medium the bremsstrahlung
 153 electron gets into. $n = 1$ means bremsstrahlung electron only crossed into one differ-
 154 ent medium. $n = nth$ meaning particle crossed n th different mediums.

155 To predict radiation refraction right from the particle, we only need equations 12
 156 and 13 with only one medium property. However, to track radiation pattern crossing from
 157 different mediums over time since its first emission from the particle at medium $n = 1$,
 158 the equation needs to be used with multiple $n = nth$ mediums.

159 Moreover, for wave tracking from medium $n = 1$, until the $n = nth$ medium, an
 160 important step is to calculate the wave refraction pattern at medium $n = 1$ consider-
 161 ing all asymmetries, Doppler effect, the Bremsstrahlung asymmetry in the travelling wave
 162 pattern. Once this information is known, this would be the starting wave incident di-
 163 rection for the second medium. After the calculations at the $n = 1$ medium with equa-
 164 tions 16, 17, 18, and 19, until the $n = nth$ medium only Snell's law needs to be used
 165 which is given in equations 3 and 4 for the forward peaking radiation pattern. This is
 166 also true for refracted backward peaking radiation patterns where the only difference in
 167 the equation is the inverted refractive index as the radiation propagates in the opposite
 168 direction with respect to the forward peaking lobes.

169 **4 Expected Radiation Patterns as a result of Wave Medium Cross-**
 170 **ing**

171 When bremsstrahlung electron emits radiation patterns while transiting from one
 172 medium to another medium, the radiation pattern of the forward and backward side of
 173 the particle refracts in exactly the opposite directions. Therefore, if bremsstrahlung an-
 174 gle, θ_{brem} between forward peaking radiation lobes increases where bremsstrahlung an-
 175 gle, θ_{brem} separates into its components Ω_3 , Ω_4 and $\Omega_3 \neq \Omega_4$. In addition, $\Omega_4 > \Omega_3$
 176 as radiation lobe that is described by the angle Ω_4 in bremsstrahlung asymmetric, R hence
 177 it has a lower frequency, therefore higher wavelength that makes it refract more com-
 178 pared to its other forward peaking pair described by the angle Ω_3 . The bremsstrahlung
 179 angle, θ_{brem} between backward peaking lobes should decrease as opposed to the increase
 180 in bremsstrahlung angle, θ_{brem} between forward peaking radiation lobes. This is because
 181 backward peaking radiation lobes are propagating in the opposite direction outside of
 182 the medium whereas, forward peaking lobes propagate into the new medium.

183 Overall, as sketched in figure 5, when forward peaking lobes tend towards form-
 184 ing a distorted dipole pattern because of $\Omega_3 \neq \Omega_4$. Backward peaking lobes tends to
 185 form distorted further backward peaking as a result of the decrease in bremsstrahlung
 186 angle, θ_{brem} where components that make bremsstrahlung angle, θ_{brem} are again not equal
 187 to each other. Hence, $\Omega_1 \neq \Omega_2$. Similarly, $\Omega_1 > \Omega_2$ because it has a larger wavelength
 188 and hence refracts at a larger angle.

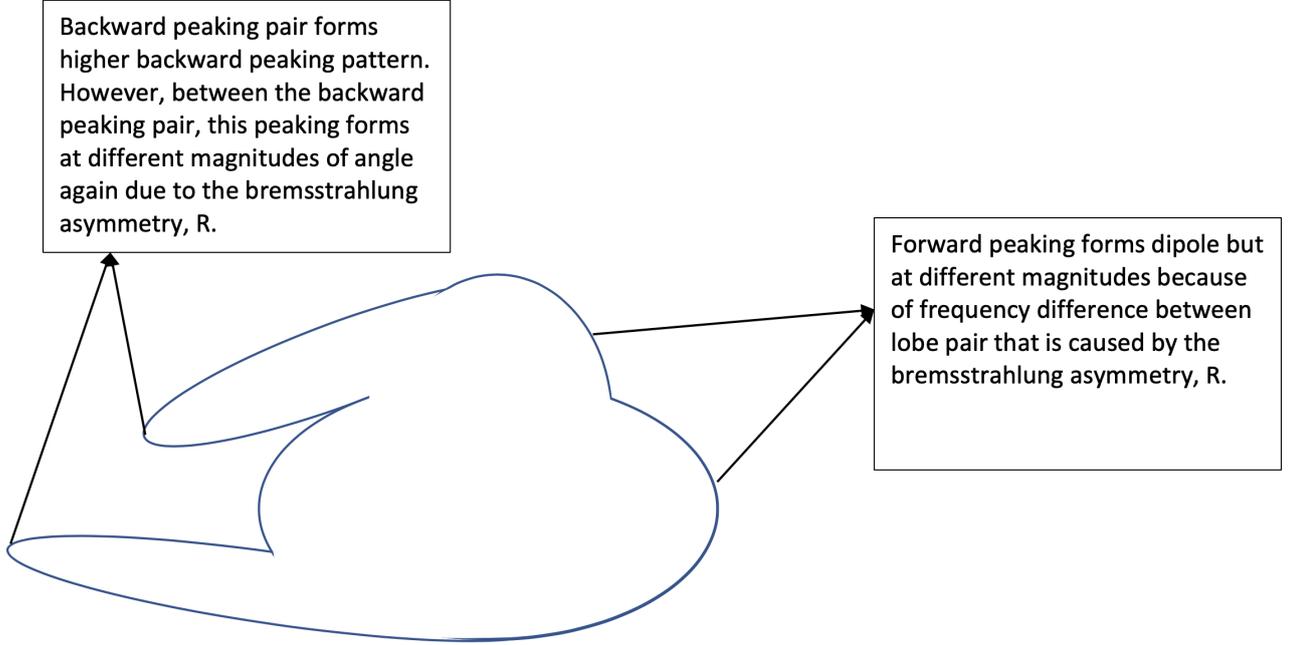


Figure 5. Sketch to show the expected overall refracted radiation pattern of the bremsstrahlung electron after transiting through one different medium. This sketch presents new generic information about the refracted radiation pattern that is expected to apply at all times for different mediums. This is not the wave track but rather important initial information required for the wave tracking. As can be seen, it is expected that forward and backward peaking radiation lobes should behave in opposite directions. So, when one leads toward dipole radiation other pair should lead more towards the direction of the particle's velocity vector (peaking). In this sketch, forward peaking tends towards a distorted dipole radiation pattern and backward lobes tend towards more peaking in the direction of the particle's velocity vector. Opposite tendencies are the result of pair lobes moving in the opposite direction where one enters into the new medium while the other lobe pair exits the new medium. Moreover, the distorted dipole tendency and backward distorted peaking tendencies are result novel symmetry break of bremsstrahlung angle, θ_{brem} into individual different angles $\Omega_1, \Omega_2, \Omega_3, \Omega_4$ where, $\Omega_3 + \Omega_4 = \theta_{brem-BetweenForwardPair} \neq \Omega_1 + \Omega_2 = \theta_{brem-BetweenBackwardPair}$. The cause of this new novel symmetry break of bremsstrahlung angle, θ_{brem} is the bremsstrahlung asymmetry parameter, R, curved trajectory, and the Doppler effect.

189 5 Summary

190 When the bremsstrahlung particle was in a vacuum, peaking lobes were all equally
 191 away from the particle's velocity vector by half of the bremsstrahlung angle, $\frac{\theta_{brem}}{2}$. When
 192 bremsstrahlung particle transits between multiple different mediums, peaking lobes are
 193 all at different angles away from the particle's velocity vector where each is defined as,
 194 $\Omega_1, \Omega_2, \Omega_3, \Omega_4$ from the particle's velocity vector. This is a novel bremsstrahlung an-
 195 gle, θ_{brem} symmetry break. They are defined in equations 12 and 13 that apply to all
 196 cases.

197 Most importantly, the whole radiation emission process should be divided into frames
 198 where each frame would represent the emission of radiation for each tangential point of
 199 the particle's trajectory. Therefore, even though the emitted radiation would be distorted
 200 and would have different angles from the particle's velocity vector, all are described by
 201 the exit angles given in equations 16, 17, 18, and 19. Because of the frame perspective,
 202 the whole process restarts again with new input angles given in equations rather than
 203 using the output angles of the distorted radiation pattern from the previous frame as the
 204 new input angles for the next frame.

205 Finally, from the example in this report, forward peaking tends toward a distorted
 206 dipole radiation pattern and backward lobes tend more peaking in the direction of the
 207 particle's velocity vector. The opposite tendencies should always be the case, however,
 208 it is medium and particle trajectory that defines whether either forward or backward peak-
 209 ing lobes would tend towards refracted dipole radiation pattern or peak more in the di-
 210 rection of the particle's velocity vector.

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 214 The Maple worksheets used to simulate the particle trajectory, external lightning leader
 215 tip electric field, particle velocity, bremsstrahlung radiation pattern in high density medium
 216 and the radiation patterns are openly available from the University of Bath Research Data
 217 Archive.

218 References

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 224 doi.org/10.1029/2020JD033204