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The mechanism of the origin the NBE (CID) and the initiating event (IE) of lightning due to the volume phase wave of EAS-RREA synchronous ignition of streamer flashes

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The Mechanism

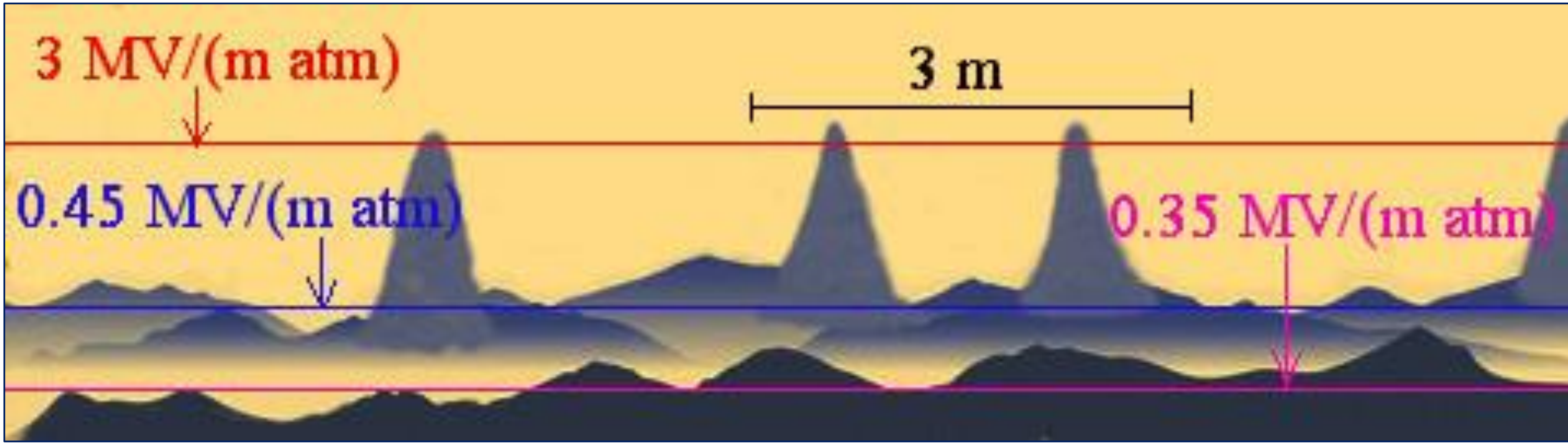
(EAS-RREA Ignition Streamer Flashes)

Kostinskiy, A., T. Marshall, and M. Stolzenburg (2019) arXiv:1906.01033

1. **We propose a mechanism for the appearance of lightning after initiation by NBEs (narrow bipolar events) or weaker initiating events (IE), in a turbulent cloud with strong local electric fields**
2. **These initial events are a volume of positive streamers initiated by the EAS-RREA phase wave of relativistic particles and gamma photons**
3. Due to ionization-heating instability , unusual plasma formations (UPFs) appear along the trajectory of streamers, which are combined into long hot plasma channels
4. Interaction of plasma channels that are formed close to each other leads to formation of three-dimensional plasma networks
5. Interaction of three-dimensional plasma networks leads to a series of breakdowns that are the source of initial breakdown pulses (IBPs)
6. Successive breakdowns along the extending path eventually make a conductive channel that can support a stepped leader process

Landscape of the electric field needed for many streamer flashes in about 1 μs (NBE/CID)

Kostinskiy et al., 2019, arXiv:1906.01033



Hydrodynamic and statistical processes in a thundercloud can create such an electric field landscape

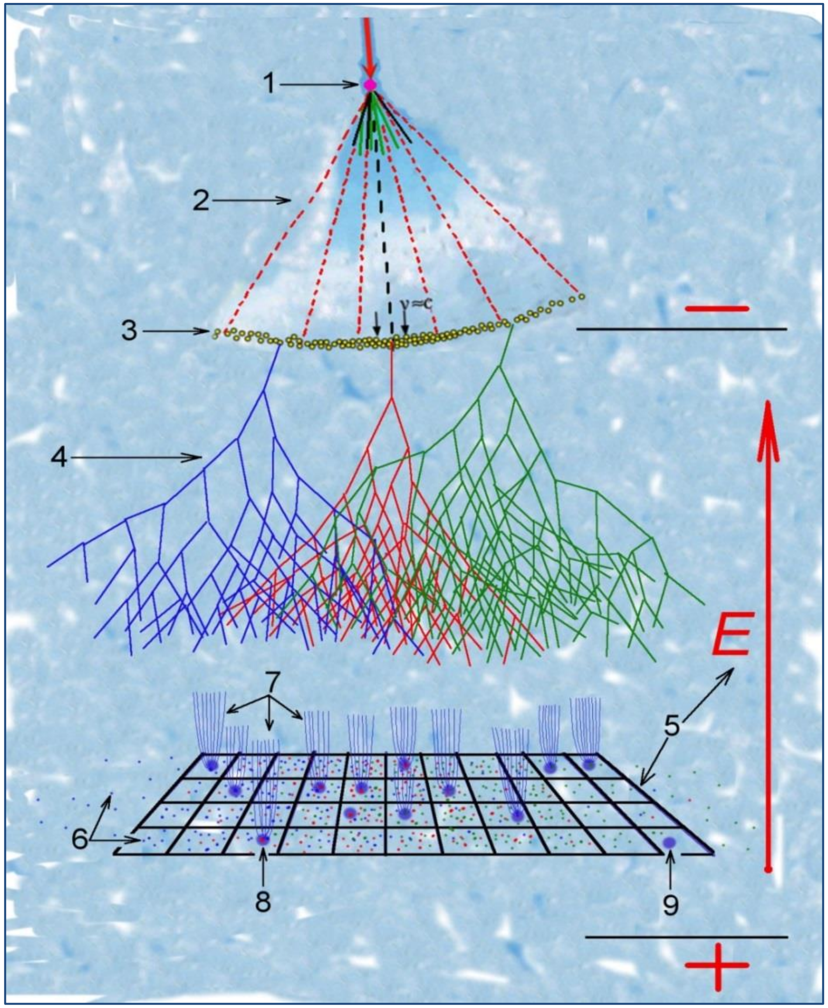
(*Colgate, 1967; Trakhtengerts, 1989; Trakhtengerts et al., 1997; Mareev et al., 1999; Iudin et al., 2003; Iudin, 2017; Brothers et al., 2018*)

Requirements of the Mechanism of the initiation of lightning

The origin of streamer flashes requires:

- Areas of 2-10 cm in size (from Meek's criterion) with fields E≥ 3 MV/(m·atm) are required for ***initiation of streamers*** (“air electrode”, E_{th}*-volume)*
- Areas of 10–100 m in size with electric fields Em ≥ 0.45–0.5 MV/(m·atm) are needed to ***maintain movement of streamers***
- The ***first electrons*** are create by cosmic rays (EAS, at altitude of 5-20 km)
- *Without a conductive plasma channel, only* ***relativistic particles*** *can provide a speed of* $0.5 - 1 \cdot 10^8 \frac{m}{s}$

"Ignition" of the EAS-RREA phase wave of streamer flashes by relativistic particles with a speed of $\approx 10^8$ m/s



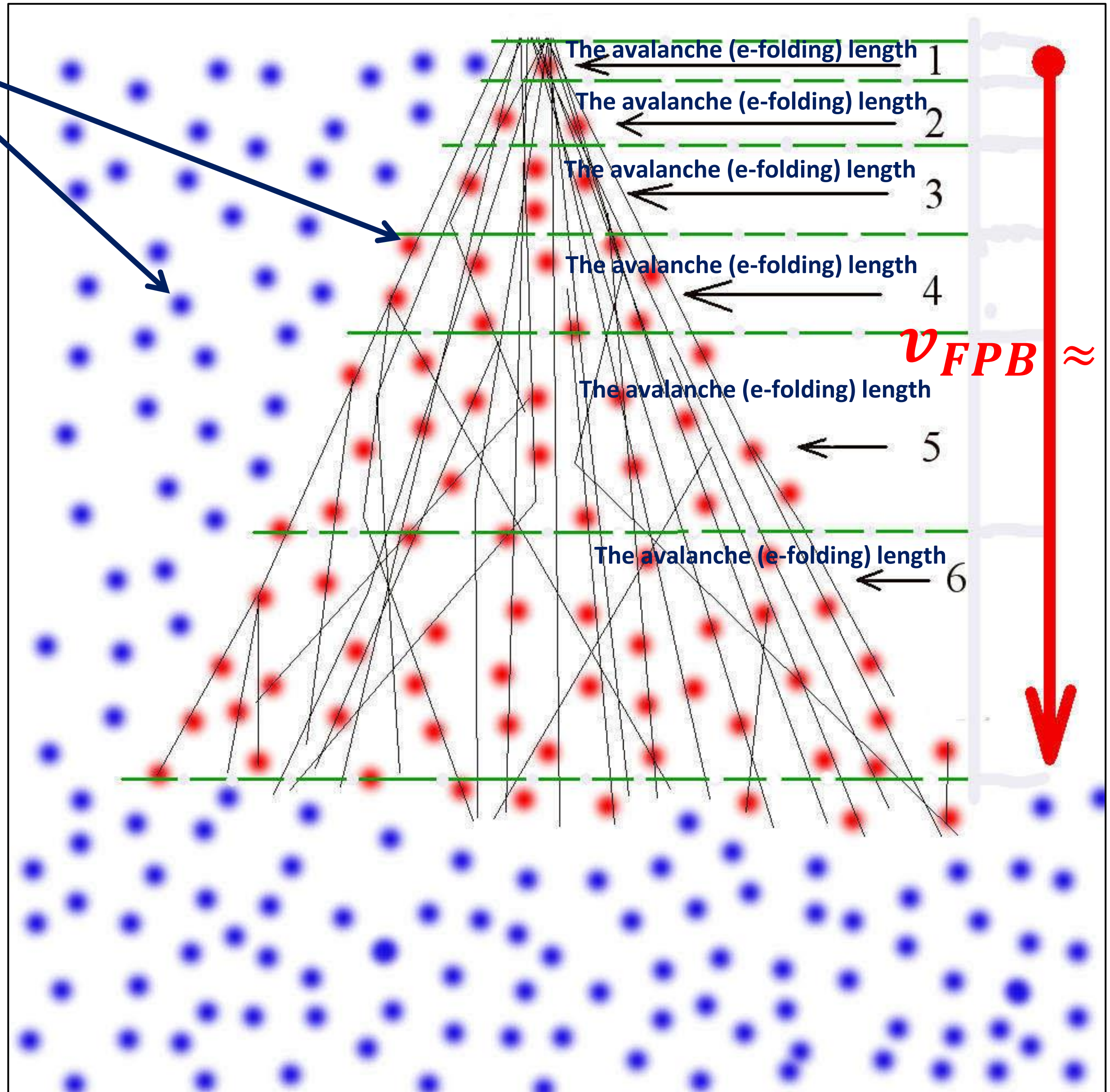
1 - the primary particle of EAS; 2 – EAS; 3 - secondary EAS; electrons; 4 – RREA; 5 - region of a strong electric field; 6 - EAS-RREA electrons crossing the region of strong turbulence of a thundercloud, which creates strong electric fields; 7 - EAS-RREA synchronized streamer flashes; 8 - an "air electrode" (E_{th}-volume) that crossed an energetic electron; 9 - an "air electrode" that has not crossed an energetic electron

"Ignition" of the EAS-RREA phase wave of streamer flashes by relativistic particles with a speed of $\approx 10^8\ m/s$ (fragment)

$E_{th} \geq 3\ \frac{MV}{m \cdot atm}$

"Air electrode"

$v_{str} \approx 10^6\ \frac{m}{s}$



$v_{FPB} \approx 10^8\ \frac{m}{s}$

Estimate of the dynamics of the occurrence and initiation of avalanches inside air electrodes due to background cosmic rays

$$\frac{dN_{ae}}{dt} = a - \nu_{ae} \cdot N_{ae} \ ,$$

N_{ae} is the number of air electrodes [L^{-3}], t is the time [S], a is the rate of formation of air electrodes due to turbulence, statistical fluctuations of the electric field, amplification of the electric field by hydrometeors [$L^{-3}S^{-1}$], ν_{ae} is the frequency of death of air electrodes [S^{-1}]. In a first approximation, we consider the rates of formation and death of air electrodes to be constant.

The solution to this equation will be

$$N_{ae} = N_{ae}^{0} e^{-\nu_{ae} t} + \frac{a}{\nu_{ae}} (1 - e^{-\nu_{ae} t})$$

N_{ae}^{0} is the number of “air electrodes” at the time of EAS arrival. In $\sim$150 ms, this equation reaches the stationary solution:

$$N_{ae} \approx \frac{a}{\nu_{ae}} . \quad \frac{a}{\nu_{ae}} \approx 1.$$

Size k_M and lifetime τ_{ae} of "air electrodes" depending on altitude

The Townsend's ionization coefficient α_{eff} in air is well described by the interpolation formula (Raizer, 1991, p. 57)

$$\alpha_{eff} = 8.892 \cdot 10^{-2} \cdot (1.233 \cdot E - 32.2)^2 \; ; \; \alpha_{eff}[cm^{-1}]; \; E\left[\frac{kV}{cm}\right]$$

The Meek's criterion, depending on the altitude will grow exponentially with height

$$k_M[cm] \approx \frac{20}{\alpha_{eff} \cdot exp\left(-\frac{h}{8.4}\right)} \approx \frac{20 \cdot exp\left(\frac{h}{8.4}\right)}{\alpha_{eff}} .$$

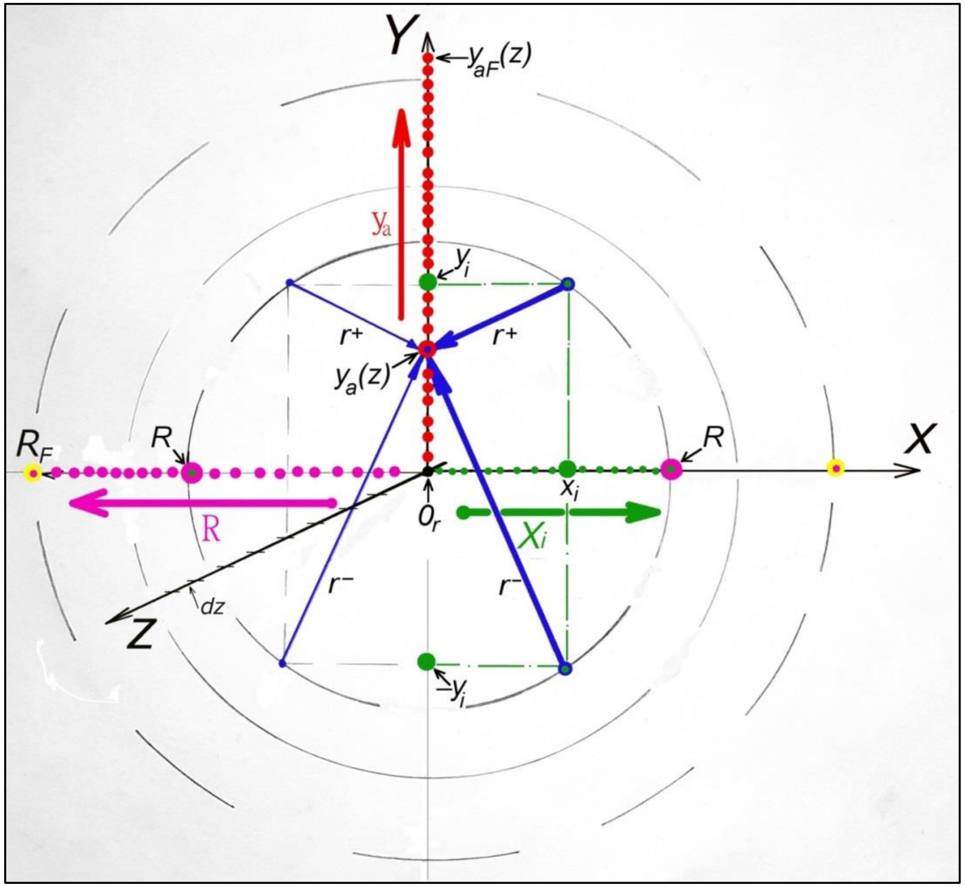
The frequency ν_{ae} and average ionization time τ_{ae} of the air electrode depending on the altitude will vary in proportion to the exponential squared and inversely to the fourth power of the electric field

$$\nu_{ae} = \nu_{cm^2} \cdot \frac{\pi (k_M)^2}{4} = \nu_{cm^2} \cdot \frac{3.97 \cdot 10^4 \cdot \left(exp\left(\frac{h}{8.4}\right)\right)^2}{(1.233 \cdot E - 32.2)^4} \; ; E\left[\frac{kV}{cm}\right] , h[km], \quad \tau_{ae} = \frac{1}{\nu_{ae}} .$$

ν_{cm^2} is the cosmic ray incident frequency (cm^2), (EXPACS, Sato (2015))

km	E [kV/(cm atm)]	E [MV/(m atm)]	α_{eff} [cm^{-1}]	$k_M[cm]$	$\nu_{cm^2}[\frac{1}{cm^2 s}]$	ν_{ae} $[s^{-1}]$	$\tau_{ae}[s]$
0	30	3	8,36	2,39	0,038	0,17	5,85
6	30	3	8,36	4,88	1,46	27,26	0,037
9	40	4	26,06	2,24	5,03	19,80	0,050
13	45	4,5	48,31	1,95	10,60	31,66	0,031
16	50	5	77,13	1,742	12,25	29,20	0,034

Scheme for calculating the flow of electrons crossing the region of a thundercloud with a strong electric field (EE-volume)



The green arrow and green dots along the positive part of the *x* axis show the order of variation of the coordinate x_i of a circle of radius *R* (first cycle), which allows us to calculate the number of seed EAS electrons sending electrons to the point $y_a(z)$; the pink arrow and pink dots along the negative part of the *x* axis show the order of variation of the radius *R* (second cycle), which allows us to calculate the sum of all electrons at the point $y_a(z)$; the red arrow and red dots along the positive part of the y axis show the order of variation of the coordinate of the point $y_a(z)$, in which the electron flux is calculated (third cycle); thick blue arrows show the distance r^+, r^- in equation (*, p.11) from the points (x_i, y_i^+), (x_i, y_i^-) to the point $y_a(z)$; symmetrical thin blue lines show the distances from the points (x_i^-, y_i^+), (x_i^-, y_i^-) to the point $y_a(z)$.

Radial (lateral) distribution of the avalanche of relativistic electrons (RREA)

Dwyer (2010), Babich & Bochkov (2011) calculated using the Monte Carlo method the radial (lateral) distribution of the avalanche of relativistic electrons (RREA), which was initiated at a point by one or more initial electrons:

$$\Phi_{re}^{c}(r,z) = \frac{N_0}{4\pi\left(\frac{D_\perp}{v}\right)(z-z_0)} \cdot exp\left(\frac{z-z_0}{\lambda} - \frac{r^2}{4\left(\frac{D_\perp}{v}\right)(z-z_0)}\right)[m^{-2}]$$

$$\lambda = \frac{7300\ [kV]}{\left(E-276\left[\frac{kV}{m}\right]exp\left(-\frac{h}{8.4}\right)\right)}$$

$\frac{D_\perp}{v} = exp\left(\frac{h}{8.4}\right)(5.86 \cdot 10^4)E^{-1.79}[m]$, E [kV/m]; $v = 0.89c; h\ [km]$

The NKG approximation is used for EAS characteristic estimation (Kamata & Nishimura, 1958):

$$\rho_e(R) = \frac{N_e^{EAS}}{R_M^2} \cdot C(s) \cdot \left(\frac{R}{R_M}\right)^{s-2} \cdot \left(\frac{R}{R_M} + 1\right)^{s-4.5}$$

where $\rho_e(R)$ — is the particle density on the distance r from shower axes, N_e^{EAS} – total number of shower particle, $R_M = 79[m] \cdot exp\left(\frac{\mathrm{h}}{8.4}\right)$ – Mølier radii, s – shower age parameter and $C(s) = 0.366 \cdot s^2 \cdot (2.07 - s)^{1.25}$, *s =0.9.*

Total number of streamer flashes n_{fl} in the entire EE-volume, depending on the distance (or time)

The sum of the contribution is the electron flux of all circles R gives the total electron flux N_{y_a} at the point $y_a(z)$ (in each layer *z−z₀+dz*):

$$N_r((z-z_0)=\frac{0.361\cdot\frac{N_e^{EAS}}{R_M^2}\cdot\left(\frac{R}{R_M}\right)^{-1.1}\left(\frac{R}{R_M}+1\right)^{-3.6}}{4\pi\left(exp\left(\frac{h}{8.4}\right)(5.86\cdot10^4)E^{-1.79}\right)(z-z_0)}\cdot exp\left(\frac{(z-z_0)}{\lambda}-\frac{x_i^2+\left(\pm\left(R^2-x_i^2\right)^{0.5}-y_a(z)\right)^2}{4\left(exp\left(\frac{h}{8.4}\right)(5.86\cdot10^4)E^{-1.79}\right)(z-z_0)}\right) \qquad (*)$$

$$r^{\pm}=\left((x_i-x_a)^2+(y_i-y_a)^2\right)^{0.5}=\left((x_i)^2+(y_i-y_a)^2\right)^{0.5}=\left(x_i^2+\left(\pm\left(R^2-x_i^2\right)^{0.5}-y_a\right)^2\right)^{0.5}$$

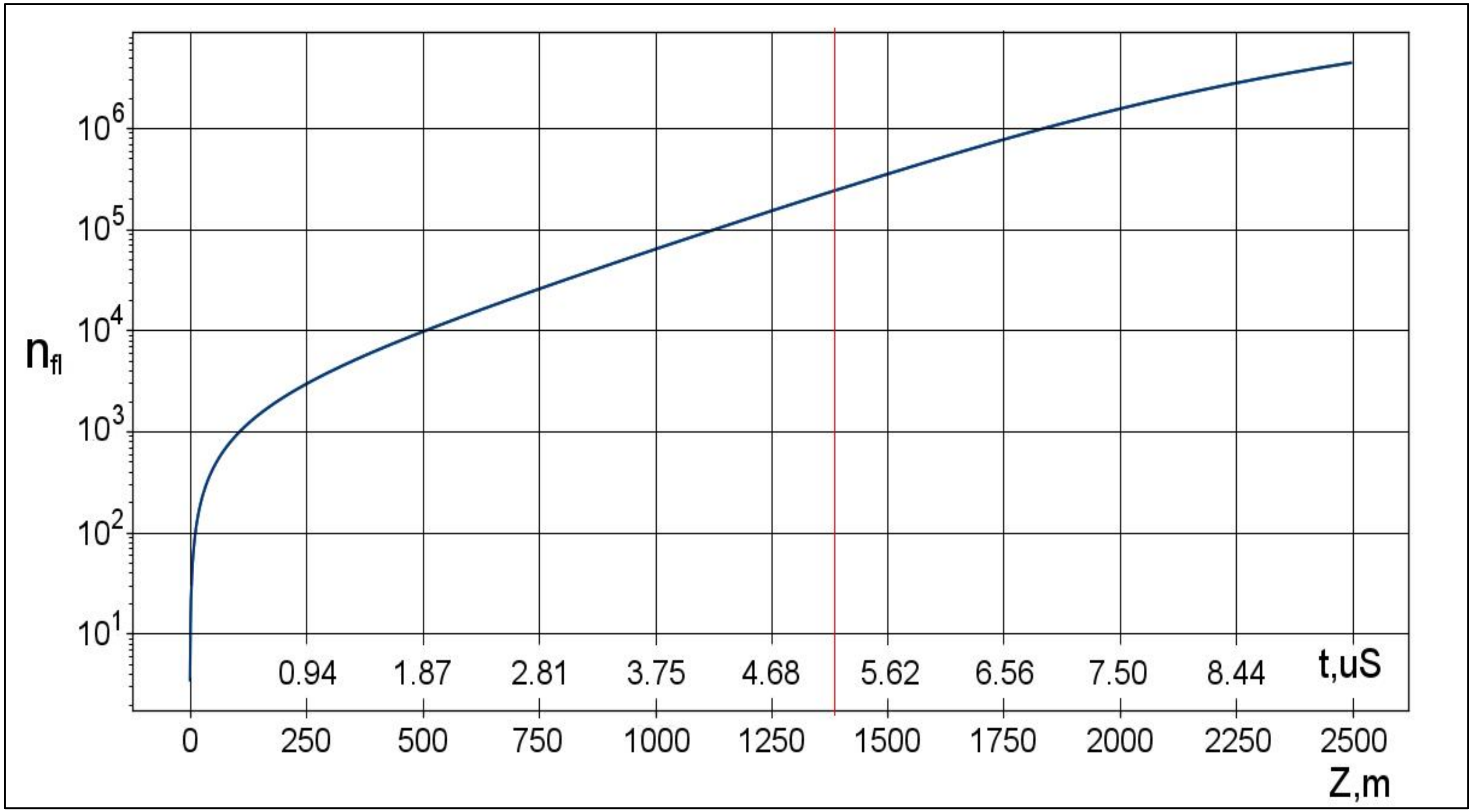
The calculated electron flux N_{y_a} at the point $(y_a(z), z-z_0)$ of the axisymmetric radial distribution in each layer of the EE-volume will be:

$$N_{y_a}(y_a(z),(z-z_0))=\int_{R=5}^{R=R_F}\int_{x=5}^{x=R}\frac{2\cdot\ 0.361\cdot\frac{N_e^{EAS}}{R_M^2}\cdot\left(\frac{R}{R_M}\right)^{-1.1}\left(\frac{R}{R_M}+1\right)^{-3.6}}{4\pi\left(exp\left(\frac{h}{8.4}\right)(5.86\cdot10^4)E^{-1.79}\right)(z-z_0)}\cdot exp\left(\frac{(z-z_0)}{\lambda}-\frac{x^2+(\pm(R^2-x^2)^{0.5}-y_a(z))^2}{4\left(exp\left(\frac{h}{8.4}\right)(5.86\cdot10^4)E^{-1.79}\right)(z-z_0)}\right)dxdR$$

The probability of such an event is calculated using the simplified Bernoulli formula and it is equal to $P_{N_{y_a}}=1-((1-p))^{N_{y_a}}$, where N_{y_a} is the flux of energetic electrons. Thus, the total number of streamer flashes in the entire EE-volume, depending on the distance (or time), we obtain by integrating the number of flashes in all layers *dz* along the *z* axis (Figure S2):

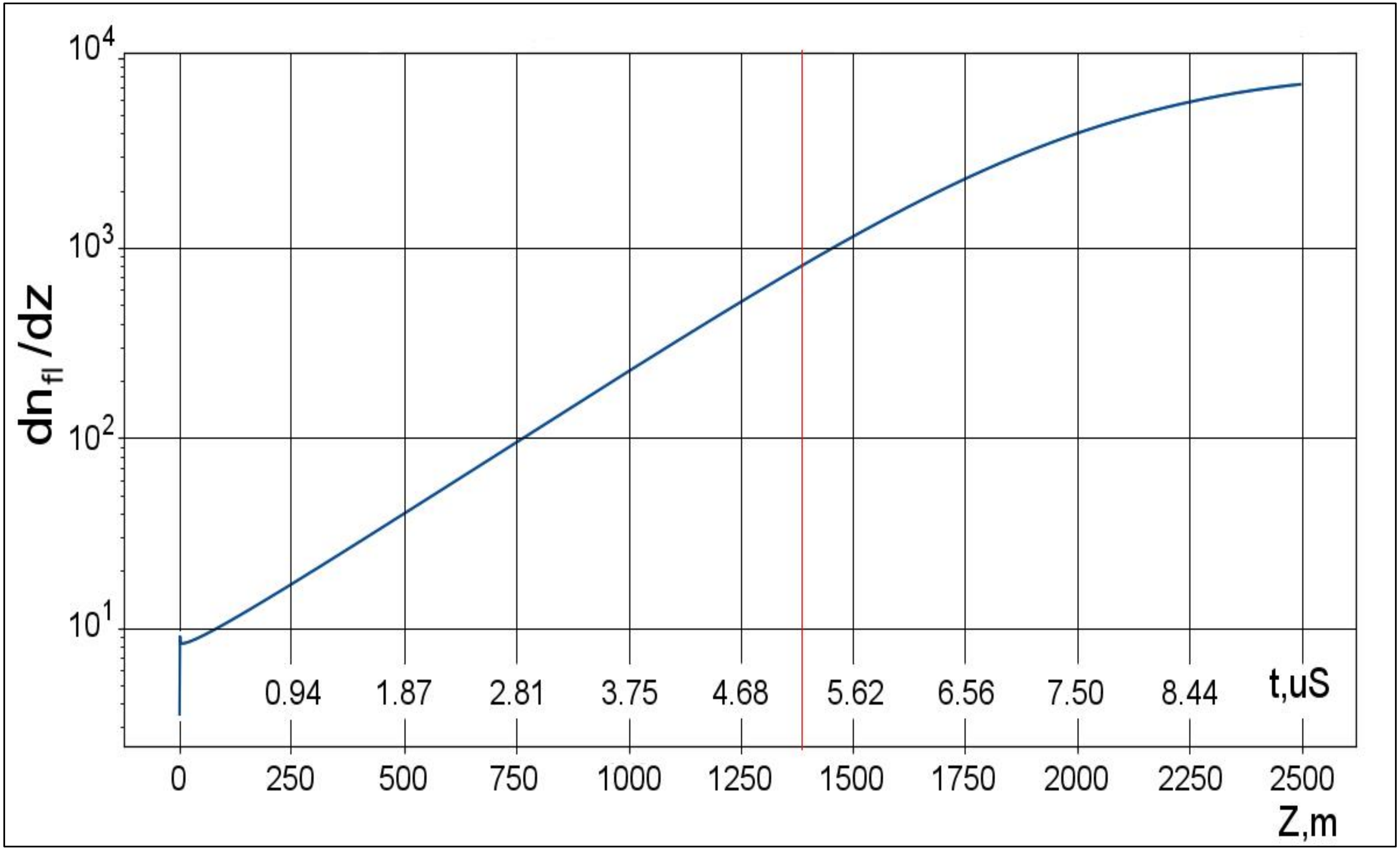
$$n_{fl}=\int_{z=z_0}^{z=z_F}\int_{y_a=5}^{y_a=y_{aF}}\rho_{E_{th}}(z,y_a(z))\cdot 2\cdot\pi\cdot y_a(z)\cdot\left(1-(1-p)^{N_{y_a}(y_a(z),z)}\right)dy_a dz$$

Estimation of the number of streamer flashes n_{fl} depending on the path *z(t)* that the EAS-RREA avalanche traverses inside the EE-volume.



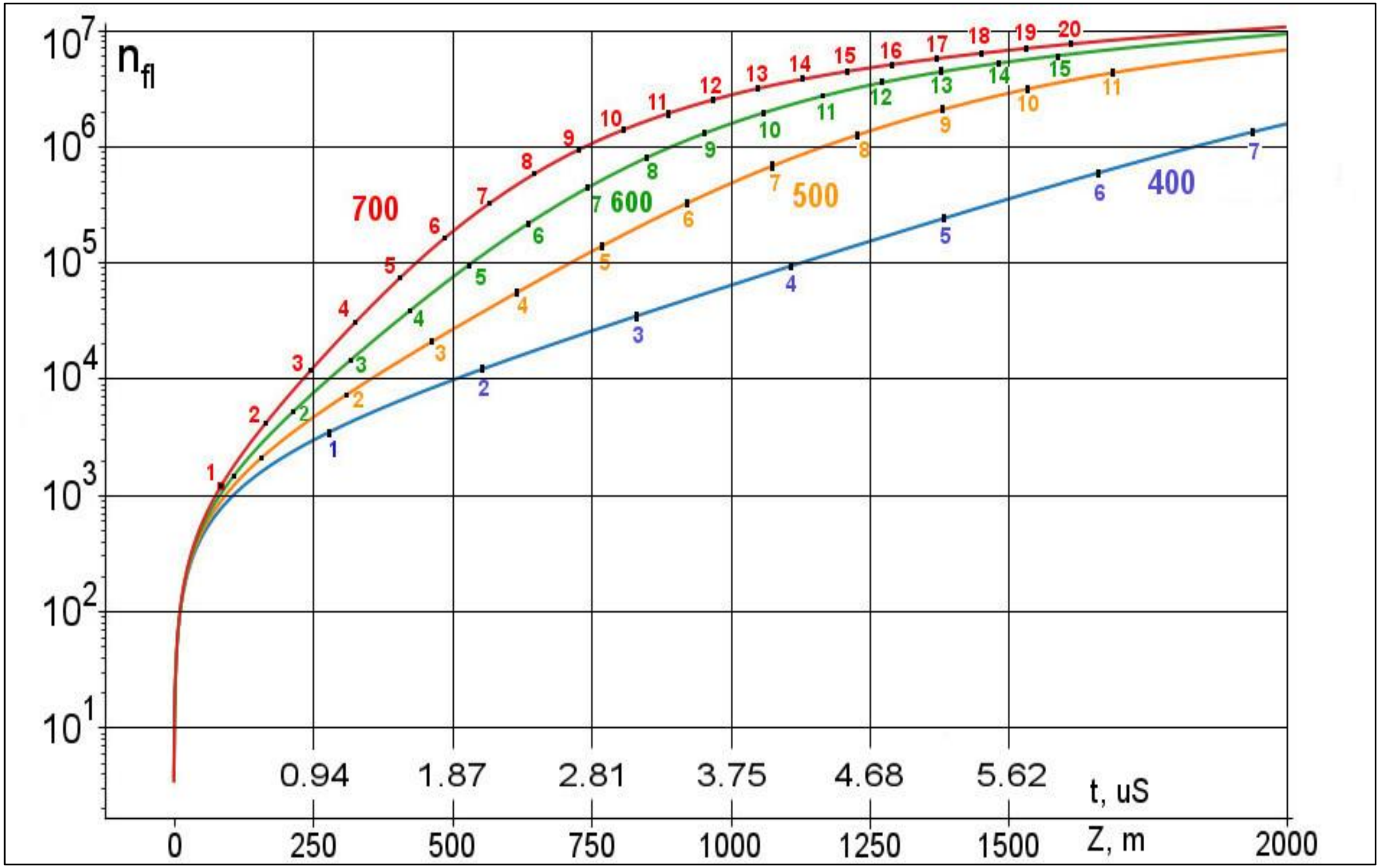
The calculation was carried out for a height of 13 km, $N_e^{EAS} = 10^6$, R_M=328 m, $400\frac{kV}{m\cdot atm}\left(85\ \frac{kV}{m}\right)$, $\lambda_{RREA} = 277\ m$, the probability of initiation of air electrodes is $\mathrm{p} = 0.001$, the density of the number of air electrodes was considered constant and equal to $\rho_{E_{th}} = 10^{-2}\mathrm{m}^{-3}$. The red vertical line shows the avalanche passage time 1385 m (5.4 µs from the beginning of the movement), which sets the volume of the EE-volume to ~1.0 км³ ($y_a(z)$=500 м.)

Number of flashes dn_{fl}/dz in each transverse air layer 1 m thick for the conditions of Figure on p.12



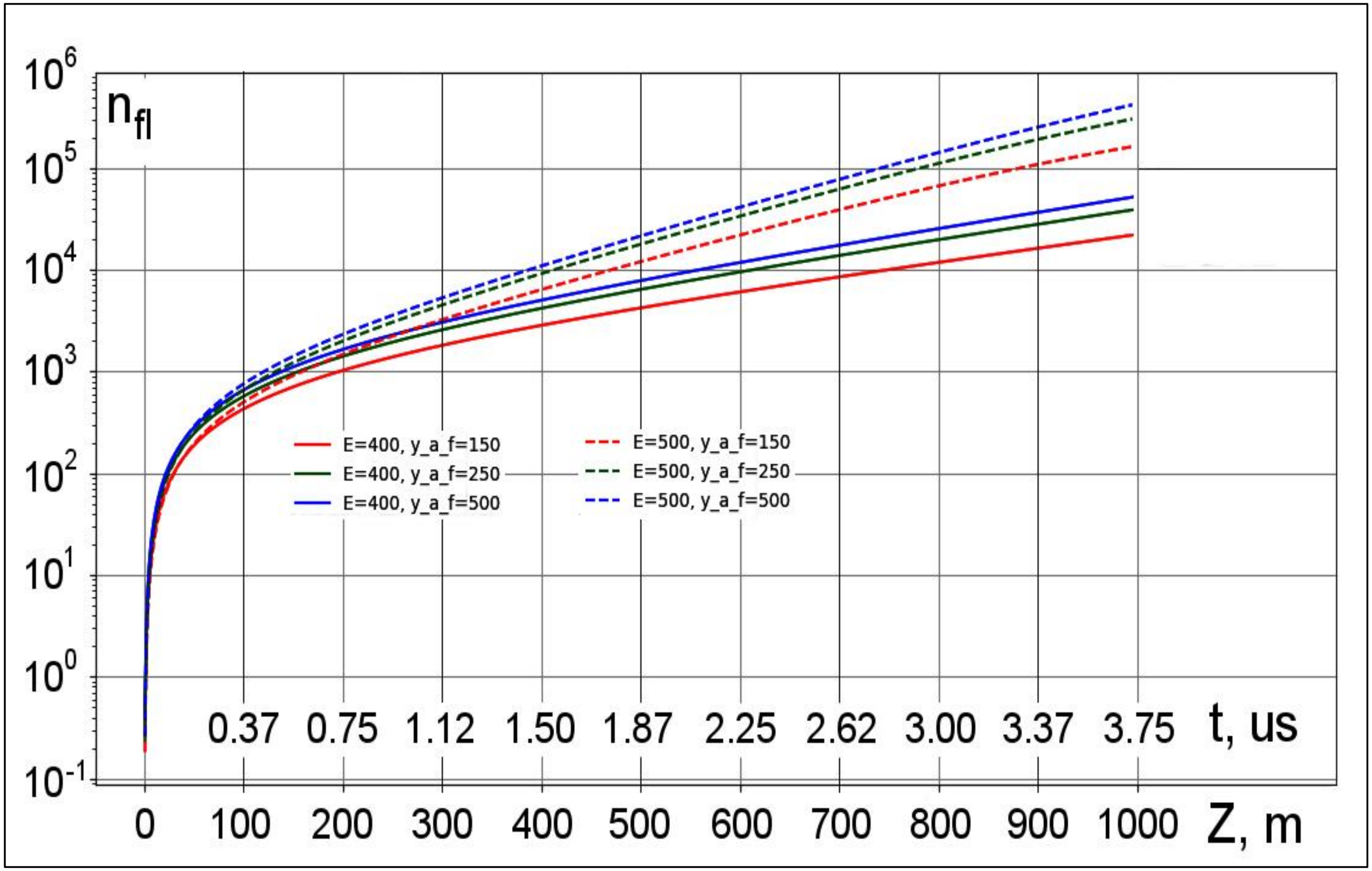
Altitude is 13 km, $N_e^{EAS} = 10^6$, R_M=328 m, $400\,\frac{kV}{m\cdot atm}\left(85\,\frac{kV}{m}\right)$, $\lambda_{RREA} = 277\,m$, $\mathrm{p} = 0.001$, $\rho_{E_{th}} = 10^{-2} m^{-3}$

Dependence of the number of streamer flashes $n_{fl}(z)$ on the electric field strength.



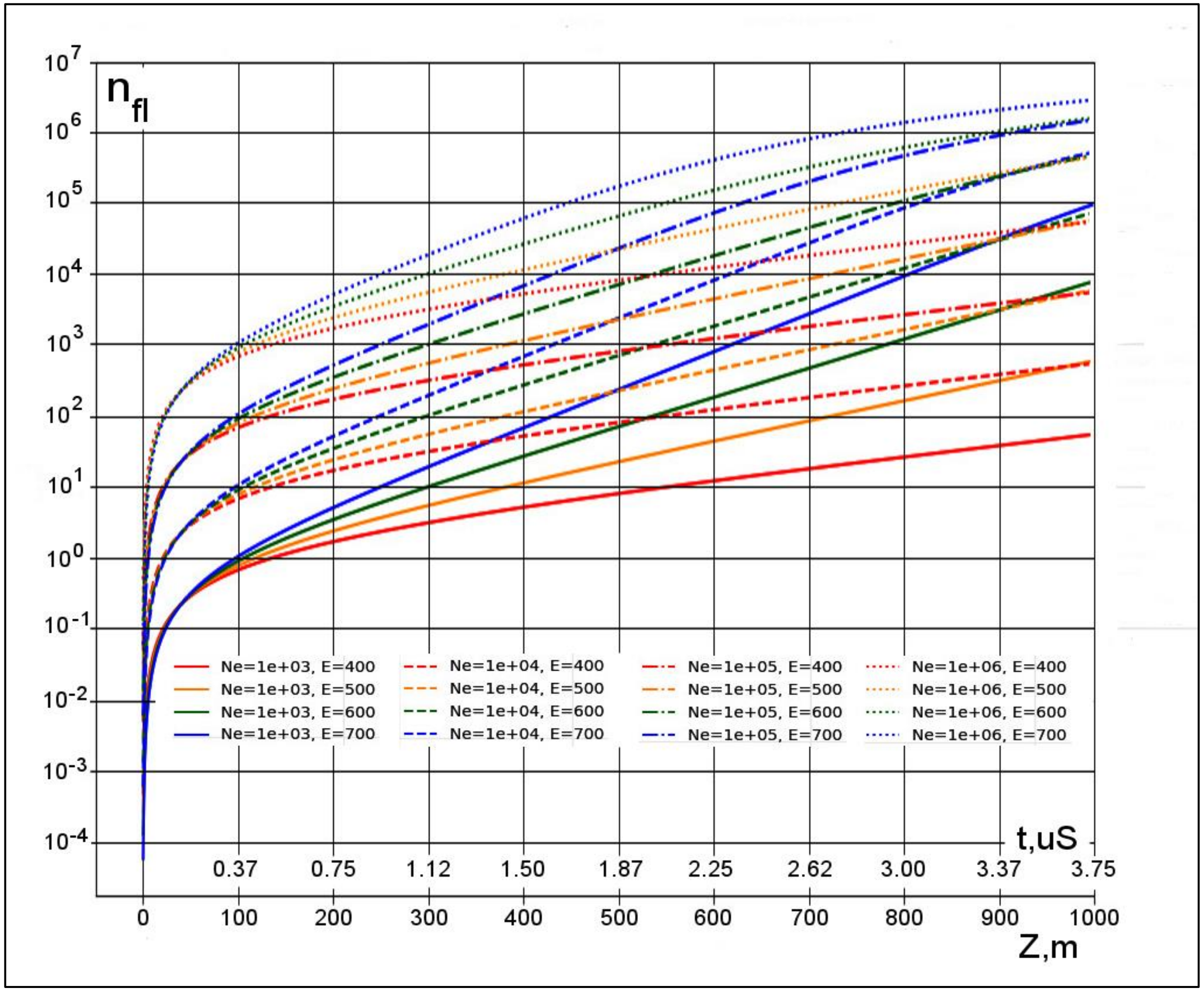
Altitude 13 km, electron hit probability is $p = 0.001(\emptyset \approx 2\ cm), \rho_{E_{th}} = 10^{-2} m^{-3}$, R_M=328 m, $N_e^{EAS} = 10^6$. The electric field took four values: $400 \frac{kV}{m \cdot atm}\left(85\ \frac{kV}{m}\right)$, $\lambda_{RREA} = 277\ m$; — blue; $500 \frac{kV}{m \cdot atm}\left(106\ \frac{kV}{m}\right)$, $\lambda_{RREA} = 153\ m$ — yellow; $600 \frac{kV}{m \cdot atm}\left(127.5\ \frac{kV}{m}\right)$, $\lambda_{RREA} = 106\ m$ — green; $700 \frac{kV}{m \cdot atm}\left(149\ \frac{kV}{m}\right)$, $\lambda_{RREA} = 81\ m$ — red. The numbers near the lines indicate the step number of the avalanche λ_{RREA}

Effect on the number of streamer flashes $n_{fl}(z)$ of volumes of the EE-volume of a thundercloud (at an altitude of 13 km), which are defined by the radii of the EE-volume



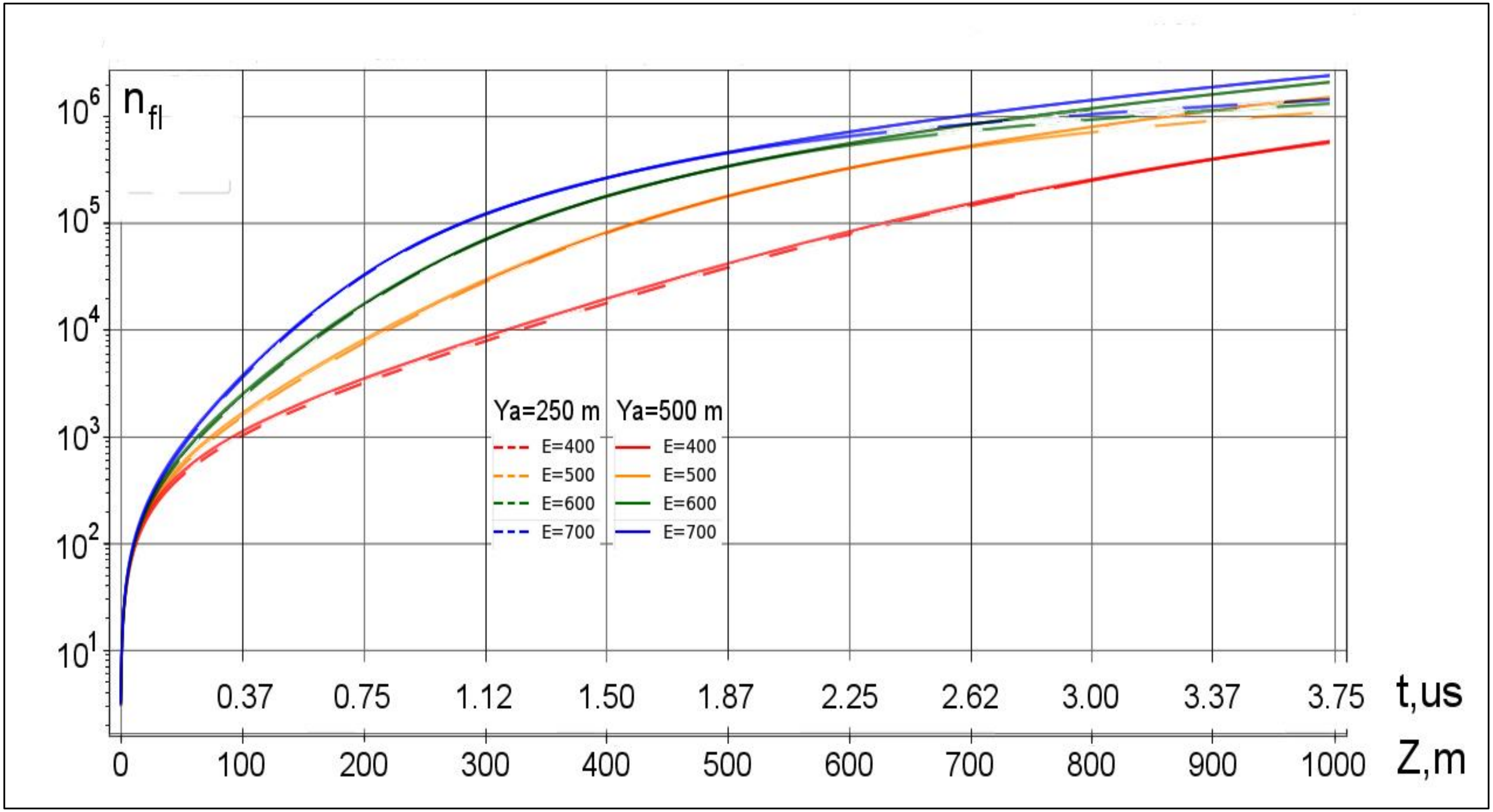
$y_{aF} = 500\,m$ (blue line), $y_{aF} = 250\,m$ (green line) и $y_{aF} = 150\,m$ (red line), for electric fields $400\frac{kV}{m\cdot atm}\left(85\,\frac{kV}{m}\right)$, $\lambda_{RREA} = 277\,m$ — solid lines, $500\frac{kV}{m\cdot atm}\left(106\frac{kV}{m}\right)$, $\lambda_{RREA} = 153\,m)$ — dashed lines. The electron hit probability is $p = 0.001(\emptyset \approx 2\,cm), \rho_{E_{th}} = 10^{-2}m^{-3}$, R_M=328 m, $N_e^{EAS} = 10^6$

Number of streamer flashes $n_{fl}(z)$ at an altitude of 13 km depending on the number of EAS seed electrons N_e^{EAS}



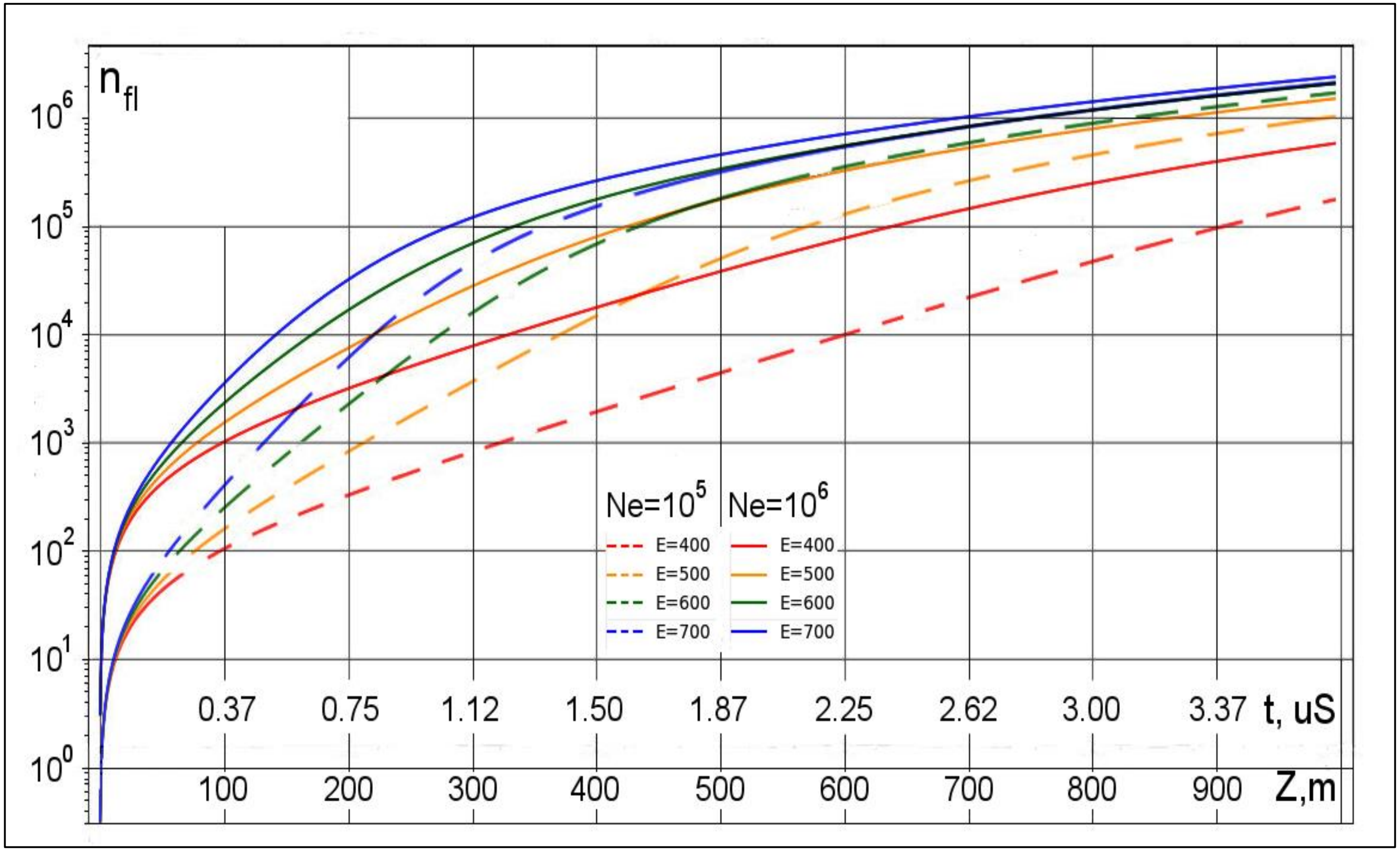
$N_e^{EAS} = 10^3 (solid\ lines)$; 10^4 (dashed lines); 10^5 (dashed-dotted lines), 10^6 (dotted lines). For each of these N_e^{EAS} values, the calculation was performed for four electric fields: $400 \frac{kV}{m \cdot atm} \left(85 \frac{kV}{m}\right)$, $\lambda_{RREA} = 277\ m$ — red; $500 \frac{kV}{m \cdot atm} \left(106 \frac{kV}{m}\right)$, $\lambda_{RREA} = 153\ m$ — yellow; $600 \frac{kV}{m \cdot atm} \left(127.5 \frac{kV}{m}\right)$, $\lambda_{RREA} = 106\ m$ — green; $700 \frac{kV}{m \cdot atm} \left(149 \frac{kV}{m}\right)$, $\lambda_{RREA} = 81\ m$ — blue. Height is 13 km, probability of electron hit is $p = 0.001 (\emptyset \approx 2\ cm)$, $\rho_{E_{th}} = 10^{-2} m^{-3}$, R_M=328 m.

Influence of the sizes of the EE region of a thundercloud (altitude 6 km, $N_e^{EAS} = 10^6$) on the number of streamer flashes $n_{fl}(z)$



The dimensions of the EE region are determined by the radii $y_{aF} = 250\ m\ (dashed\ lines), y_{aF} = 500\ m\ (solid\ lines)$: $400 \frac{kV}{m \cdot atm}\left(196\ \frac{kV}{m}\right)$, $\lambda_{RREA} = 120\ m$ — red; $500 \frac{kV}{m \cdot atm}\left(244 \frac{kV}{m}\right)$, $\lambda_{RREA} = 66\ m$ — yellow; $600 \frac{kV}{m \cdot atm}\left(294\ \frac{kV}{m}\right)$, $\lambda_{RREA} = 46\ m$ — green; $700 \frac{kV}{m \cdot atm}\left(343\ \frac{kV}{m}\right)$, $\lambda_{RREA} = 35\ m$ — blue. The electron hit probability is $p = 0.001(\emptyset \approx 2\ cm)$, $\rho_{E_{th}} = 10^{-2} m^{-3}$, R_M=161 .

Number of streamer flashes $n_{fl}(z)$ at an altitude of 6 km depending on the number of EAS seed electrons N_e^{EAS}



$N_e^{EAS} = 10^5(dashed\ lines),\ 10^6(solid\ lines)$. For each of these values N_e^{EAS} the calculation was performed for four electric fields: $400\frac{kV}{m\cdot atm}\left(196\ \frac{kV}{m}\right),\ \lambda_{RREA} = 120\ m$ — red; $500\frac{kV}{m\cdot atm}\left(244\frac{kV}{m}\right), \lambda_{RREA} = 66\ m$ — yellow; $600\frac{kV}{m\cdot atm}\left(294\ \frac{kV}{m}\right), \lambda_{RREA} = 46\ m$ — green; $700\frac{kV}{m\cdot atm}\left(343\ \frac{kV}{m}\right), \lambda_{RREA} = 35\ m$ — blue . The probability of electron hit is $p = 0.001(\emptyset \approx 2\ cm)$, $\rho_{E_{th}} = 10^{-2} m^{-3}$, R_M=161 m.

Conclusions

- In the case of validity of our Mechanism, only an EAS-RREA avalanche with the number of seed particles $N_e^{EAS} > 10^5$ can provide the necessary number of electrons and positrons for the synchronous initiation of streamer flashes providing a VHF signal accompanying powerful NBE over the entire range of altitudes above sea level
- Even when evaluated from below, EAS-RREA avalanches with the number of electrons $N_e^{EAS} \approx 10^5 - 10^6$ in electric fields (400-700 kV/(m·atm)) provide the necessary electron flux for simultaneous synchronization in for several microseconds of many streamer flashes in the EE-volume
- If the proposed Mechanism is correct, then the NBE energy spectrum should be continuous and go over to IE parameters
- If the Mechanism is correct, then a detailed study of the NBE parameters at different altitude can provide information on the most powerful turbulent flows inside a thundercloud (possibly opposed and differently charged)

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