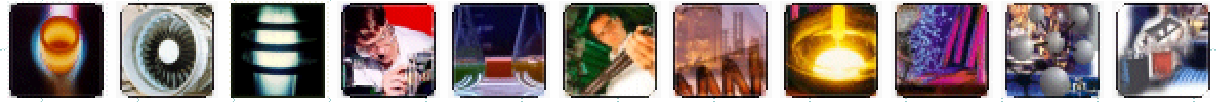


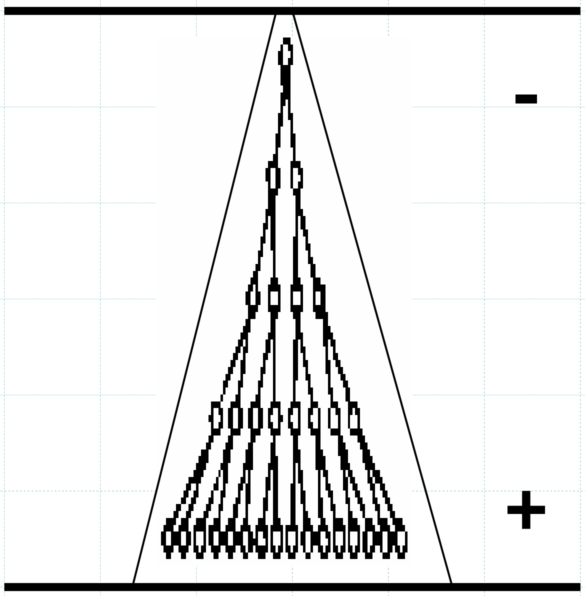
Synergetic Description of Streamer Discharge

A.Chirokov, A.Gutsol, A.Fridman

- Avalanches in Townsend Dark Discharge and transition to Glow Discharge
- Streamers vs. Avalanches Meek’s Condition
- Effect of Vibrational Excitation

2 September 2004

Avalanches



$$1 = \gamma(\exp(\overline{\alpha} d) - 1)$$

Avalanche in Air:

d = 3 mm

alpha*d = 10-14

E = 3e4 V/cm

We = 1e7 cm/sec

Wp = 1e5 cm/sec

T = d/We = 30 ns

Diff = 1e3 cm2/sec

Width = sqrt(4*Diff*T) = 0.01 cm

N = exp(alpha*d) = exp(10) = 1e4

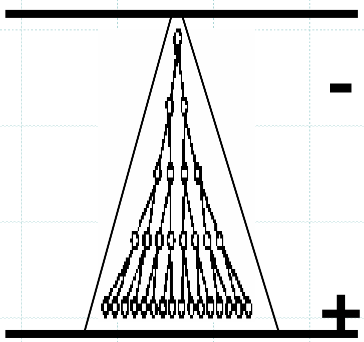
j = 1e-9 A / 1e-4 cm2 = 1e-5 A/cm2

FACT:

Dark Townsend discharge current density

j = 1e-10÷1e-5 A/cm2

Avalanches



Maximum Townsend discharge current density

j = 1e-5 A/cm2, correspond to the case when avalanches start to overlap, then transition to glow discharge occur.

FACT:

Dark Townsend discharge current density

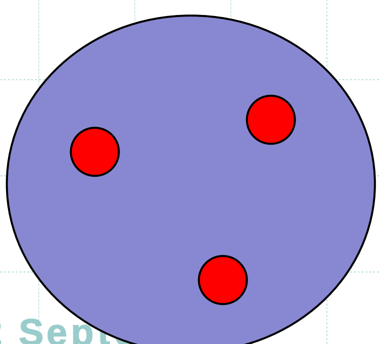
j = 1e-10÷1e-5 A/cm2

$$j = \frac{\varepsilon_0 \mu_+ E^2}{2d}$$

$$dE/dx = e(n_+ - n_-)/\varepsilon_0$$

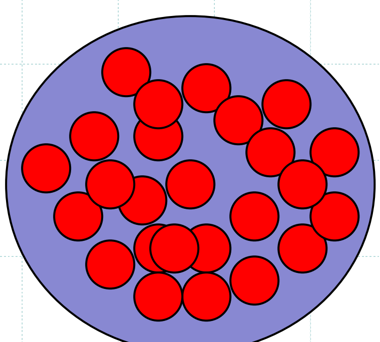
$$n_+ = j / e\mu_+ E$$

Top view of Townsend discharge



No overlapping

overlapping

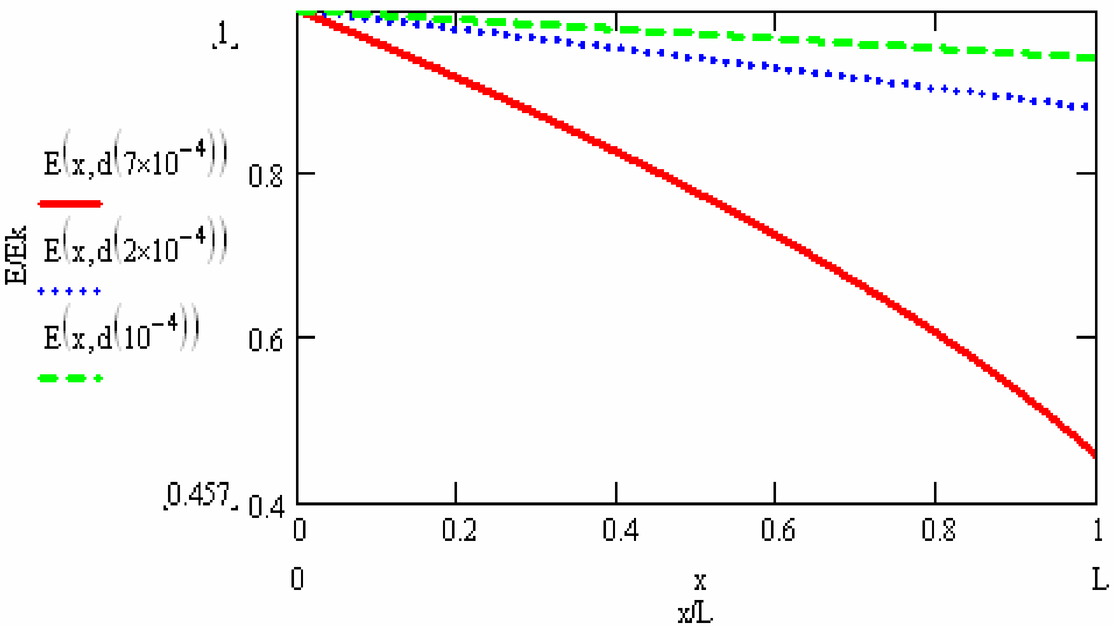


Avalanches, Transition to Glow

$$j = \frac{\varepsilon_0 \mu_+ E^2}{2d} \qquad dE/dx = e(n_+ - n_-)/\varepsilon_0$$

$$n_+ = j / e\mu_+ E$$

Space Charge
Transition prediction

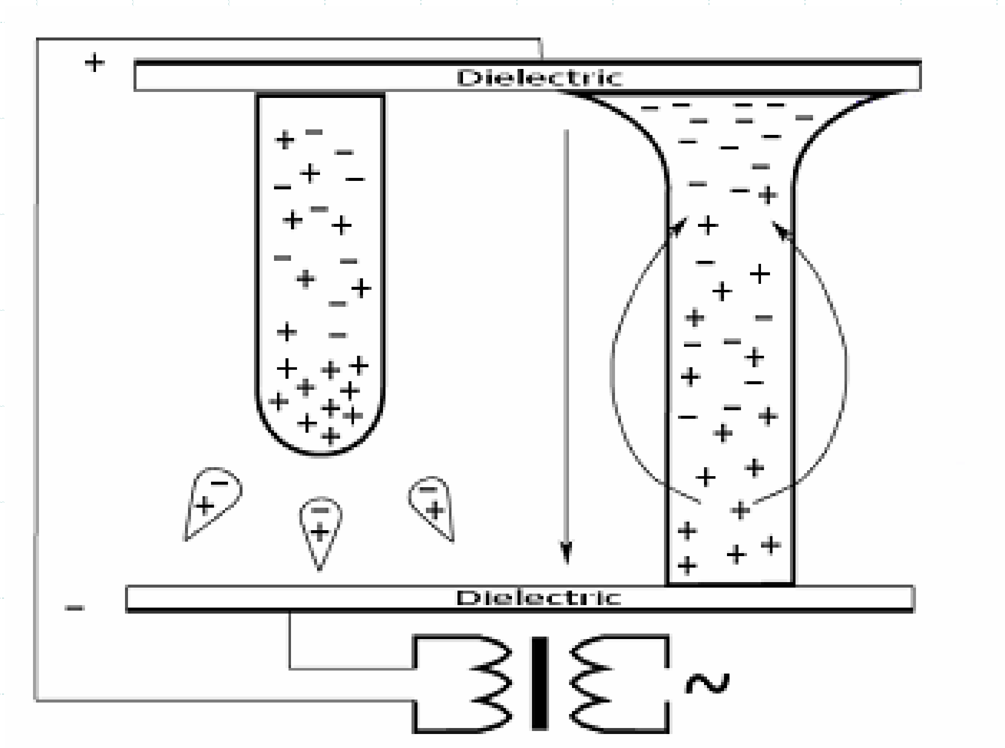


space charge predicted transition

`j transition = 1e-3 A/cm2`

`which realized at alpha*d = 14 when avalanches overlap.`

Streamer



$$R(E) = \sqrt{\frac{2 \cdot D(E) \cdot d}{W_e(E)}}$$

$$E_{str} = \frac{1}{4\pi\varepsilon_0}\frac{Q}{R^2} = \frac{RN\varepsilon}{3\varepsilon_0}$$

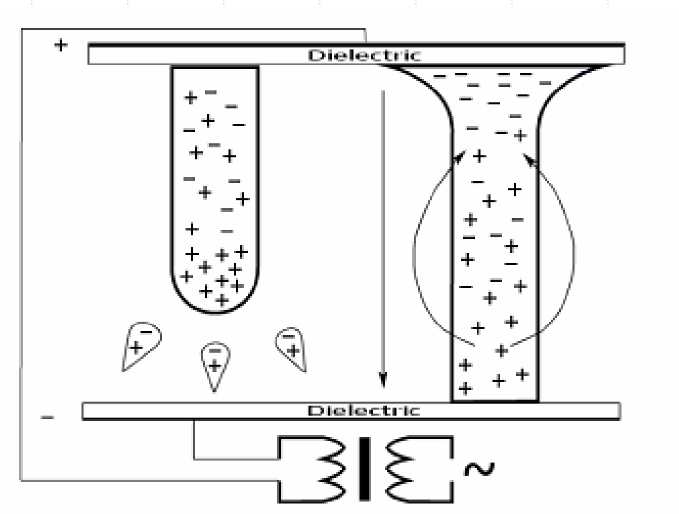
Where, $N = \alpha \exp(\alpha x) / \pi R^2$

$$E_{str} = \frac{\alpha(E)\exp(\alpha(E)d)\varepsilon}{3\pi\varepsilon_0\sqrt{\frac{2 \cdot D(E) \cdot d}{W_e(E)}}}$$

"A streamer will develop when the radial field about the positive space charge in an electron avalanche attains a value of the order of the external applied field"

J. M. Meek 15 Apr. 1940

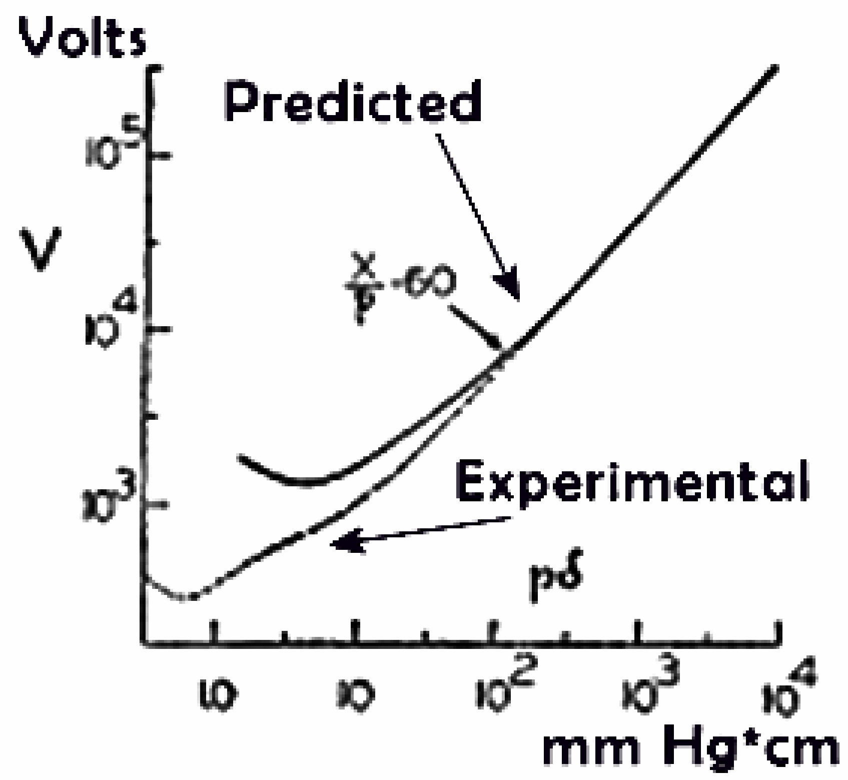
What do we know about streamer?



In air, atm pressure, 1 mm gap:

Duration	1-10 ns	Energy	10^{-7} 10^{-6} J
Radius	0.1 mm	Electron Energy	1-10 eV
Peak Current	0.1 A		
Current Density	10^{2}-10^{3} A/cm2	Electron Density	10^{14}-10^{15} 1/cm3
Total Charge	10^{-10} 10^{-9} C		

Streamer formation criteria, validation



Meek criteria

For pd>100 very good agreement with experimental data,

In our case 760*0.3 = 228 we expect good performance of Meek criteria

Meek’s condition

For air gap, 1 cm.

E = 3.296E+4 V/cm

Alpha*d = 18.622

Experimental Value E = 31.5 kV/cm

>Validation data taken from Meek’s publications

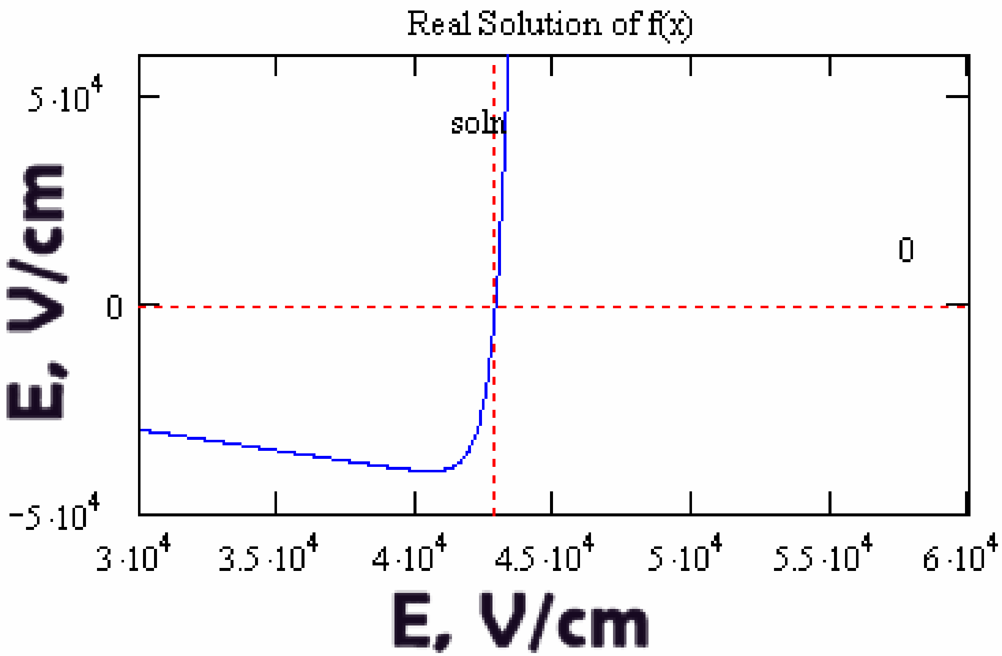
Streamer

$$E_{str} = \frac{\alpha(E)\exp(\alpha(E)d)\varepsilon}{3\pi\varepsilon_0\sqrt{\frac{2\cdot D(E)\cdot d}{W_e(E)}}}$$

Simulation of Meek's criteria

E_{str}=c*$E_{external}$

Does not depend on c, in all simulations c=1



Simulation details:

Gas: air

Gap: d = 3 mm

Results:

Alpha*d = 17.103

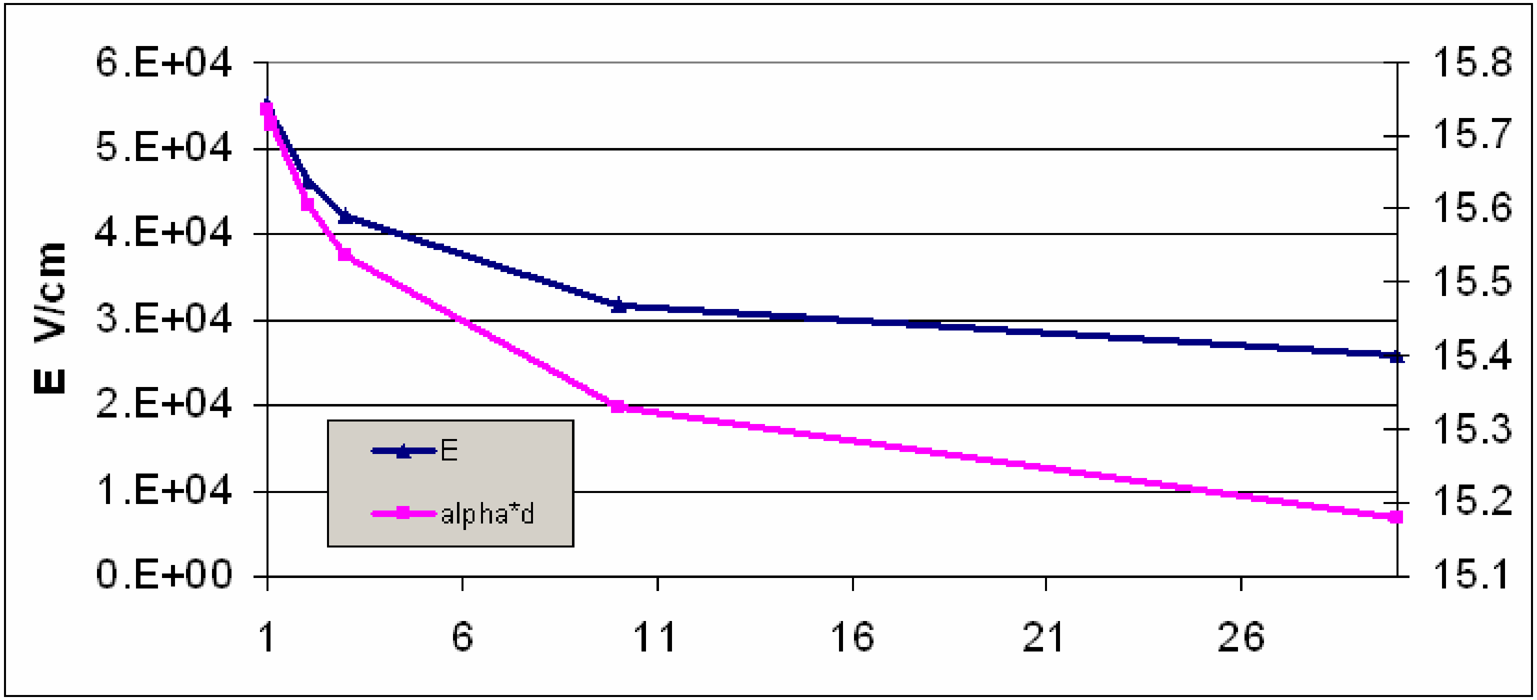
Alpha = 57.011

E = 4.284E+4 V/cm

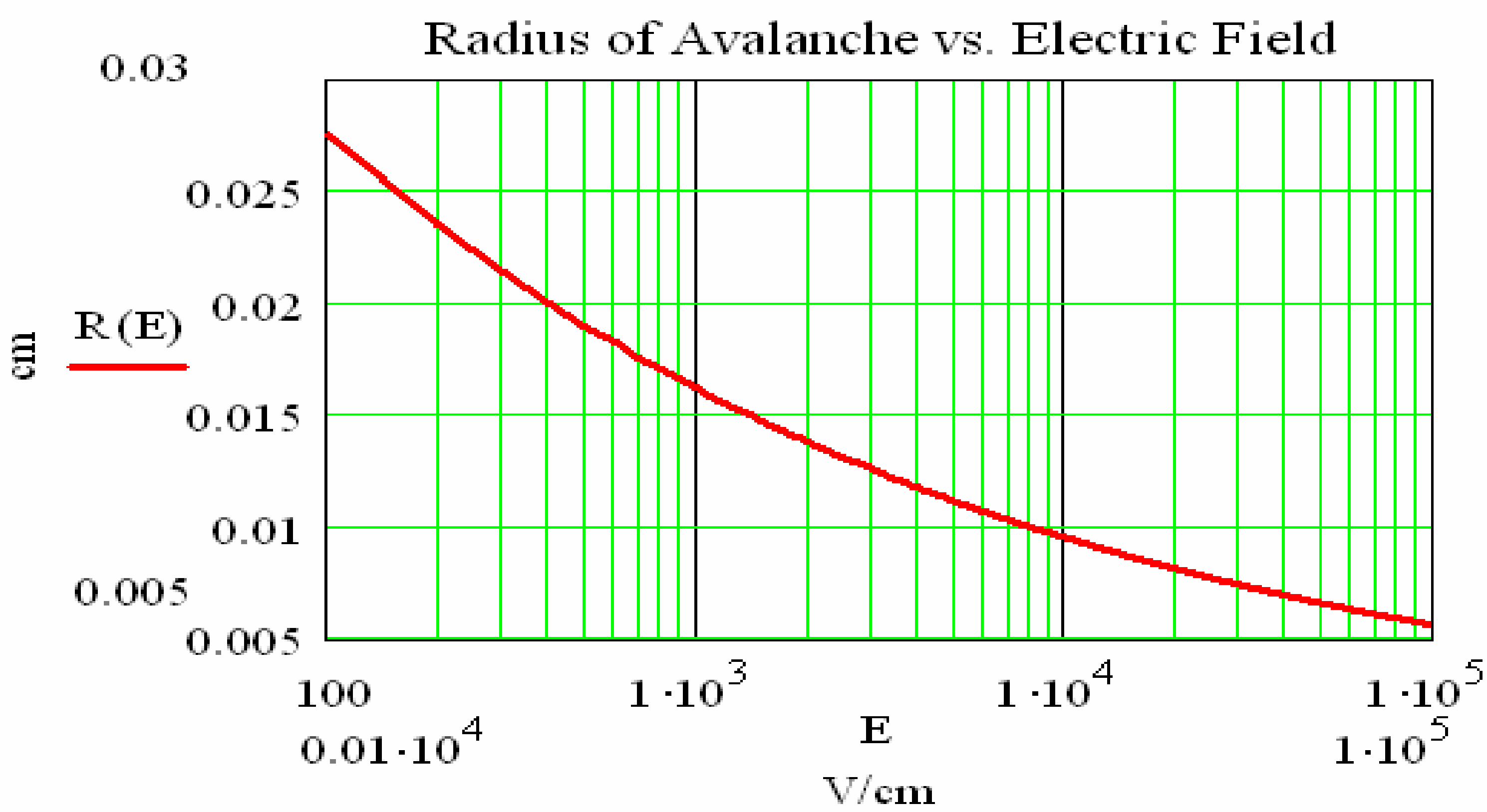
Streamer discharge with enhanced ionization

If for some reason ionization coefficient is enhanced, than electric field requirements for streamer formation slightly reduced. d = 1 mm

$$\alpha'(E) = e \cdot \alpha(E)$$



Streamer Radius Estimation vs. Electric field



Avalanches & Streamers Radius:

Increases with decrease of electric field

$$R(E) = \sqrt{\frac{2 \cdot D(E) \cdot d}{W_e(E)}}$$

Electric field and vibrational excitation

In presence of vibrationally excited species, electron kinetics constants changes by factor of phi. Value of b compiled from different sources is b = {5,6,7}

$$\varphi(T_v) = \exp(b \cdot \exp(-\frac{\hbar\omega}{kT_v}))$$

$$K_e(T_e, T_v) = \varphi(T_v) \cdot K(T_e)$$

$$\varepsilon_{vib} = \hbar\omega(\upsilon + \frac{1}{2})$$

$$E_v = \frac{\hbar\omega}{\exp(\frac{\hbar\omega}{kT_v}) - 1}$$

$$\hbar\omega(N_2) = 0.2\, eV$$

vibrational excitation

Relaxation in volume, cm^3/sec

$$R_v = k_{vt} \cdot V \cdot n_0$$

$$k_{vt} = 10^{-17}\ cm^3/\sec$$

Relaxation on wall, cm^3/sec

$$R_{wall} = 8 \cdot \frac{V \cdot \gamma \cdot D}{d^2}$$

$$\gamma = 10^{-3}$$

Vibrational Energy, J/cm^3

$$E_v = \frac{P \cdot \eta}{Q + R_{wall} + R_v}$$

Inside channel d = 0.1 mm (Relaxation)

1. Convection t=d/V= 0.01/100=1e-4 sec
2. Diffusion t=d^2/D=1e-4/0.2=5e-4 sec
3. Kinetics t = 1/kN = 1e-2 sec

Inside gap d = 1 mm

1. Convection t=d/V=10/100 = 0.1 sec
2. Diffusion t=d^2/D=1e-2/0.2=5e-2 sec
3. Kinetics t = P/hv*N = 0.1 sec

Kinetically Balanced vibrational excitation

$$P_v = k_{eV} \cdot n_e \cdot n_0 \cdot \hbar\omega \cdot V$$

$$k_{eV} = 3 \cdot 10^{-8}\ cm^3/\sec$$

vibrational excitation

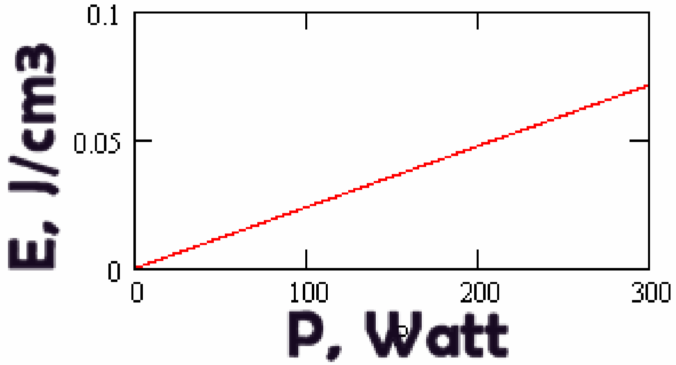
Simulation Settings:

K = 1e-17 (relaxation const)

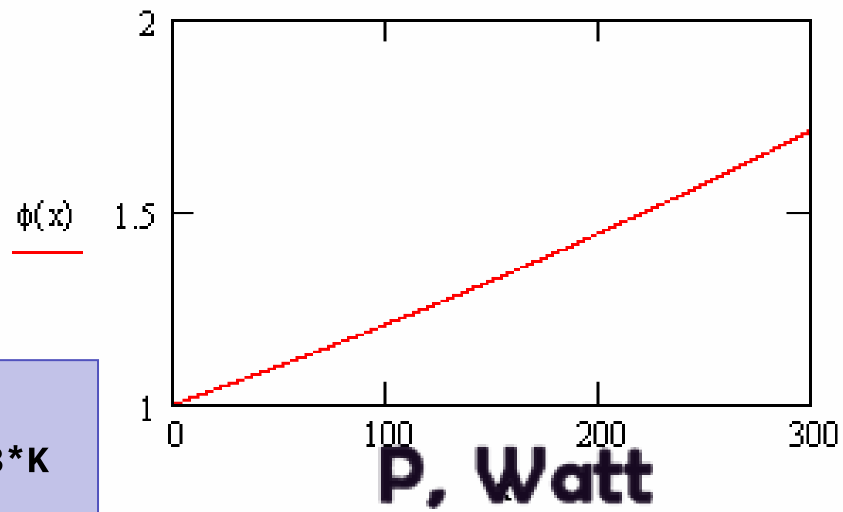
Rv = 2.687E+3 cm3/sec

Rw = 1.6 cm3/sec

Q = 250 cm3/sec



$$\varphi(E_v) = \exp\left(\frac{b}{1 + \frac{\hbar\omega}{E_v}}\right)$$



- 2.24e4 cm3 = mole (normal conditions)
- Air Cp = 7R/2 ≈ 30 J/mole*K = 0.0013 J/cm3*K
- 1 eV/molecule = 4.3 J/cm3 = 3300 K

Electric field and vibrational excitation

$$\varphi(E_v) = \exp\left(\frac{b}{1 + \frac{\hbar\omega}{E_v}}\right) \qquad b = \frac{c}{\left(\frac{E}{N}\right)^2}$$

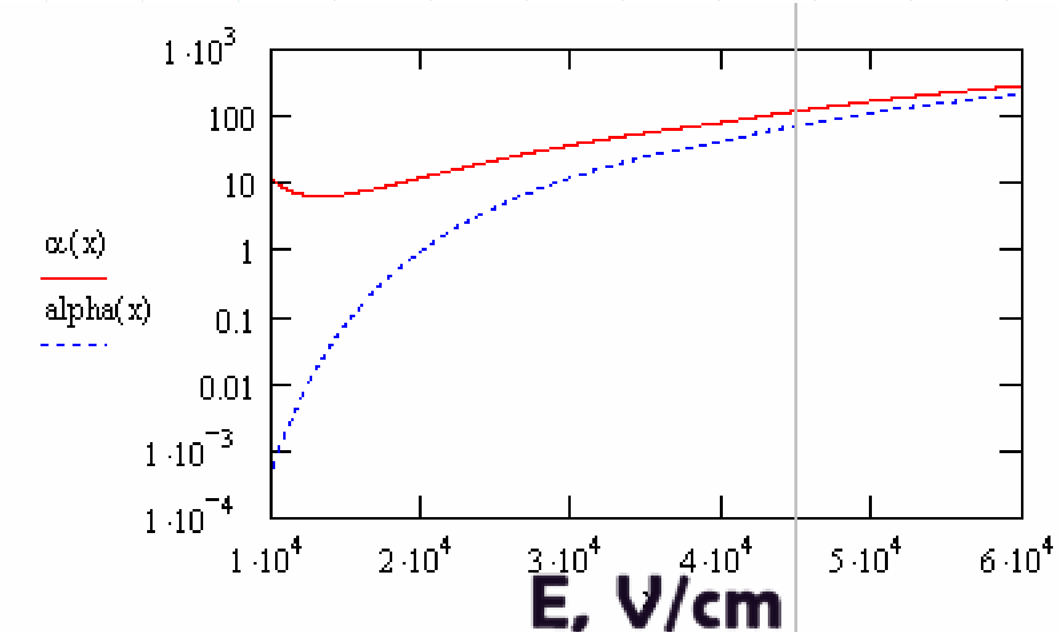
Simulation Settings:

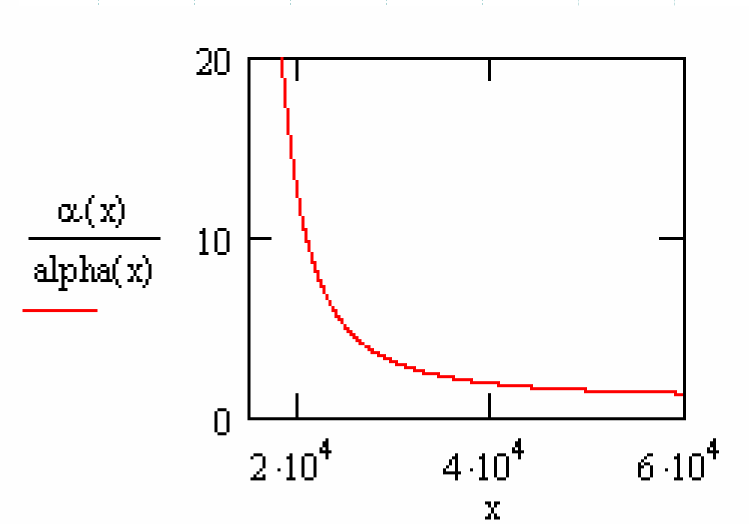
E = 4.284E+4 V/cm

E/N = 160 Td

b = 7

C = E^2*b = 16^2*7 = 1792

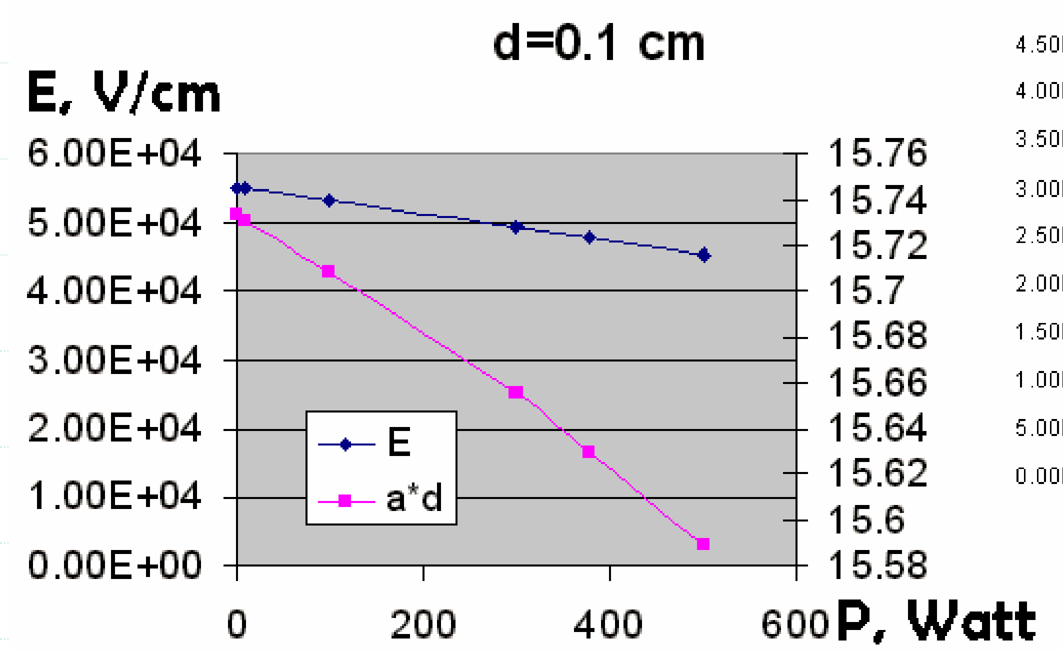


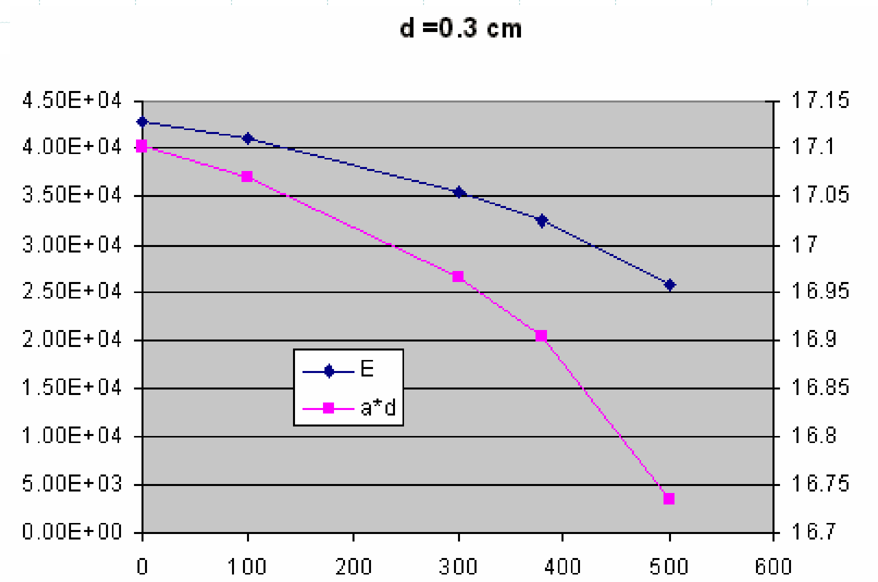


Electric field and vibrational excitation

Effect of vibrational Excitation:

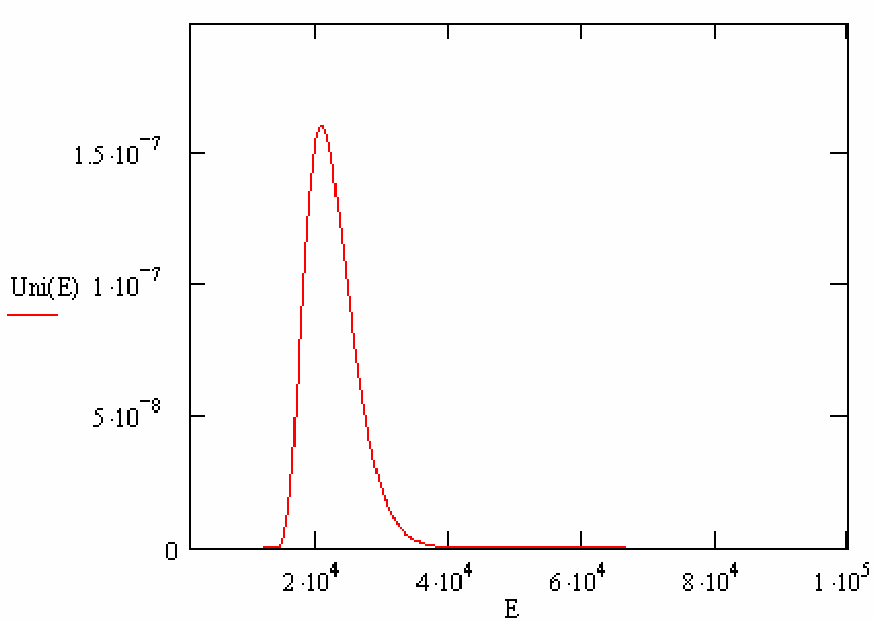
Based on figures from previous slide.



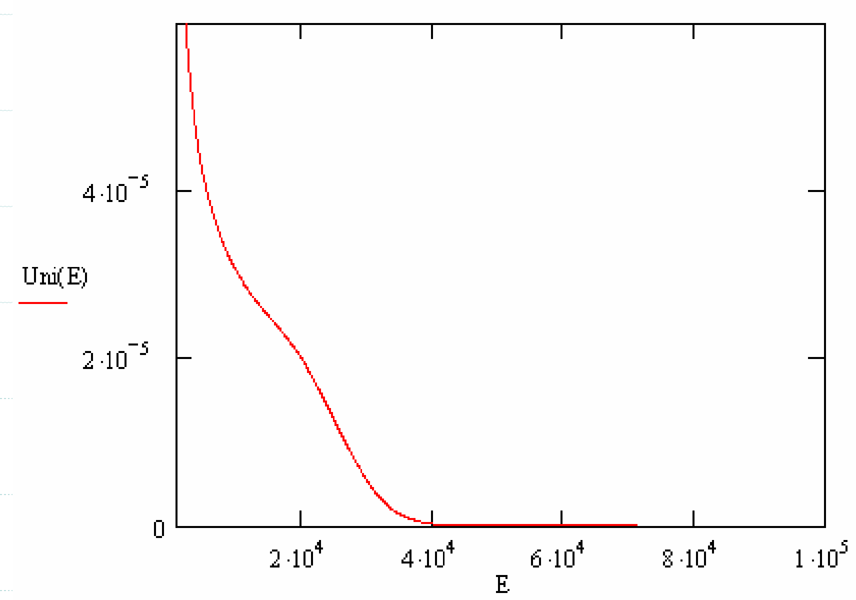


Electric field and vibrational excitation, Uniformity

d = 0.1 cm, P = 500 W



d = 0.1 cm, P = 10 W



$$\gamma = \frac{R(E)^2}{\exp(\alpha(E))}$$

Discharge uniformity estimation

Conclusions

- Vibrational Excitation which consume up to 90% of energy input allows to have discharge at lower electric field, thus making streamers thicker and less energetic.
- Having such streamers can trigger streamer overlapping and transition to glow (as in case of avalanches).
- Estimation of streamer energy and streamer radius depending on electric field and level of excitation is needed, (some equations were show in this presentation)
- Evaluation of effect of vibrational excitation as well as other effects trough EEDF calculation.