Dielectric Barrier and Corona Discharges

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Why using Corona and DBDs?

Technological motivations

Atmospheric plasma sources:
  Cost reduction
  Works in surrounding air

Chemical efficiency

O_{3} production

Flexible size

Corona and DBD
Main applications of Corona and DBD

- Flow control
- Electrostatic precipitation
- Lighting
- Ozone production
- Plasma/catalyst coupling (air treatment, solar fuels)
- Surface functionalization
- Biomedical applications

**Corona and DBD**

- Ions wind
- 3 body reactions
- Surface reactivity
- Synergy of all

**Very good to prevent gas heating**
Why Atmospheric Pressure Plasmas heat the gas?

Atmospheric pressure: \( n_{\text{gas}} \approx 2.5 \times 10^{19} \text{ cm}^{-3} \)

What is different at higher pressure?

Collision frequency increases

\[
\lambda = \frac{\langle \nu \rangle}{v_n} = \frac{1}{n_n \cdot \sigma_n}
\]

e- mean free path \( \approx 500 \text{ nm} \)

electrons collisions are mostly:

- elastic collisions (atomic gases)
- vibrational excitation (molecular gases)
How to avoid gas heating?

Very quickly, plasma is easier to sustain where it has started

Arcing, high current, strong heating

How to prevent Arcing?

- Limit the current (resistive discharge)
- Voltage pulse shorter than arc development (<100 ns)
- Strongly non uniform E field (Corona)
- Dielectric between the electrode (DBD)
Most of the time, filamentary discharges
“Discharge”: any flow of electrical current through ionized gas (extension of initial meaning)

“self-sustained” discharge = produce its own current that does not depend on any external source (UV, radioactivity, etc...)

Coronas and DBDs, are “transient” self-sustained discharges

“breakdown” ≠ “ignition” ≠ “onset”

Corona discharges especially can develop at “onset” voltage lower than “breakdown voltage”

“filament” ≠ “streamer” streamer = a breakdown mechanism

“Corona” and “DBDs” CONFIGURATIONs are reactor geometries

“DBDs” and Corona DISCHARGEs = more than just 2 types of discharges. Often developing with Townsend breakdown or Streamer breakdown mechanism
I. Breakdown mechanisms
   a) Townsend mechanism
   b) Streamer mechanism

II. Corona discharges

III. What is a Dielectric Barrier Discharge?
   a) Electrical characteristics
   b) Development of a single filament
   c) Role of the dielectric?

IV. Role of surface vs gas phase dynamics
   a) Interaction between filaments
   b) Diffuse discharges

V. Confinement and gas motion
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Townsend breakdown mechanism

Naturally \( n_e \approx 10^3 \text{ cm}^{-3} \) (radioactivity, etc...)
\[
\frac{dn}{dx} = \alpha n \cdot dx
\]
\[
n(x) = n_0 \exp(\alpha x)
\]
\[
j_-(x) = j_-(0) \exp(\alpha x)
\]

\( \alpha \) – number of ionization acts from 1 e- drifting in E per unit of length
\[
\frac{\alpha}{p} = A \exp\left(-B \frac{p}{E}\right)
\]

\( \alpha \) is a steep function of \( E/n_g \)

\[\text{Fig. 4.3. Ionization coefficients for a wide range of } E/p \text{ values (a) in molecular gases, (b) in inert gases. From [4.3] }\]
\[\text{Y.P. Raizer, Gas Discharge Physics, Springer Verlag}\]
Townsend breakdown mechanism

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n(x) = n_0 \exp(\alpha x) \\
j_-(x) = j_-(0) \exp(\alpha x)
\]

\( \alpha \) – number of ionization acts from 1 e⁻ drifting in E along 1 cm

\[
\frac{\alpha}{p} = A \exp\left(-B \frac{p}{E}\right)
\]

\( \gamma \) – number of secondary e⁻ produced per ion hitting the cathode surface per second

in electronegative gases, loss of e⁻ from attachment have to be taken into account: \( \alpha \rightarrow \alpha_{\text{eff}} = \alpha - \eta \)
Townsend breakdown mechanism

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Townsend breakdown mechanism

No significant potential distortion

Bad Honnorf, 9/30/2016
O. Guaitella – DBDs and Coronas
Avalanche to glow transition

Difficult to stabilize at atmospheric pressure because of constriction and heating.
Outline

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   a) Townsend mechanism  
   b) Streamer mechanism

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Streamer growth mechanism

Naturally, \( n_e \approx 10^3 \text{cm}^{-3} \) (radioactivity, etc...)

\[
n(x) = n_0 \exp(\alpha_{\text{eff}} x)
\]

What happens if the amplification is very efficient (large \( \alpha \))?
Streamers growth mechanism

Naturally \( n_e \approx 10^3 \text{ cm}^{-3} \) (radioactivity, etc…)

\[
n(x) = n_0 \exp(\alpha_{\text{eff}} x)
\]

What happens is the amplification is very efficient?

- On short time scale e- drift away from ions (higher mobility)
- space charge → field distortion

How much charge for disturbing \( E_0 \)?

Breakdown field in air \( \approx 30 \text{ kV/cm} \)
Mean free path \( \approx 0.5 \mu\text{m} \)
Ionization length \( (\alpha^{-1}) \approx 50 \mu\text{m} \) \( (\alpha^{-1}) \)

In order to have \( E_0 \approx E' \) : **Meek criterion**

\[
E'' \approx \frac{e \cdot N_e}{4\pi \varepsilon_0 R^2} \quad \Rightarrow \quad N_e \approx \frac{4\pi \varepsilon_0 (\alpha^{-1})^2 \cdot E_0}{e} \approx 5 \cdot 10^8 \text{ cm}^{-3}
\]
Streamer growth mechanism

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n(x) = n_0 \exp(\alpha_{\text{eff}} x)
\]

What happens is the amplification is very efficient?

- On short time scale \( e^- \) drift away from ions (higher mobility)
- Space charge \( \rightarrow \) field distortion
- When \( 1e^- \rightarrow N_e \approx 10^8 \) (Meek criterion) \( |\vec{E}_{\text{ind}}| \approx |\vec{E}_a| \)
- \( \alpha \) increases very fast with \( E \rightarrow \) secondary avalanches are very efficient
Streamers growth mechanism

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- On short time scale e- drift away from ions (higher mobility)
- Space charge \( \rightarrow \) field distortion
- When \( 1e^- \rightarrow N_e \approx 10^8 \) (Meek criterion) \( |\vec{E}_{ind}| \approx |\vec{E}_a| \)
- \( \alpha \) steep function of \( E \rightarrow \) secondary avalanches are very efficient
- "positive" streamer: need for electrons in front of streamer head... photoionization?
Streamer growth mechanism

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- \( \alpha \) increases very fast with \( E \rightarrow \) secondary avalanches are very efficient
- For “positive” streamer: need for upfront electrons... photoionization?
- Quasi neutral column is growing, space charge is moving further
- Streamer growth is much faster than e⁻ drift velocity

A streamer is not “propagating”, it’s “growing”
Positive and negative streamer

where are positive and negative electrodes?

Bourdon et al, Plasma Sources Sci. Technol. 19 (2010) 034012

Streamers in nature: sprites

Main difference: contact with electrodes and/or dielectric
About Streamer breakdown...

- Growth duration: 1-10 ns
- Radius: 100-200 µm
- Current density: 100-1000 A.cm\(^{-2}\)
- Electron density: \(10^{14}-10^{15}\) cm\(^{-3}\)
- Mean Electron Energy: 1-10 eV

- Negative streamer wider and slower than positive ones

- Initial charge density?
- Necessity for photo-ionization?
- Branching mechanism?
- ...

?
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V. Confinement and gas motion
Various geometries for producing Corona discharges

Strongly Non-uniformed applied electric Field...

The Aerial World, by Dr. G. Hartwig, London, 1886. P. 310
Corona discharges: principle

\[ \int_{0}^{x_1} (\alpha(x) - \eta(x)) \, dx = \ln \left( 1 + \frac{1}{\gamma} \right) \]

- Ionization occurs only in the active zone
- The current is collected at the ground via ion drift only \( I = k \cdot U(U - U_0) \)
- The potential between the electrode is very weakly disturbed by the plasma ignition in the active zone
- Active zone increases with \( U \)
Corona discharges

- Burst Corona
- Streamer Corona
- Glow Corona
- Spark

“Positive Corona”

“Negative Corona”

Trichel pulses Corona
Pulseless Corona
Spark

Corona discharges: Trichel pulses

- Ionization can occur only in the active zone

1. A space charge starts to build up

2. However, charge density is too low and $E_a$ is not shielded

3. The positive cloud collapses

- The process restarts to produce the next “Trichel pulse”

- Frequency is proportional to the current
If the space charge is strong enough (i.e., charge density high enough), $E_o$ is shielded at the tip, streamer growth starts. Why is the streamer stopping in the drift zone?

- Streamer is not an ideal conductor
- Potential in the head decreases with distance

$$\text{Streamer corona}$$

$$R = \frac{\rho \cdot \ell}{S}$$
About Corona discharges...

- Partial breakdown discharges in non uniform field
- Different discharges simply by adjusting the current
- Ions drift in the weak field zone
- Streamer stops because of its own resistivity
- Risk of spark at low voltage (leader mechanism)
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Many different geometries of DBDs

Any geometry, but at least 1 dielectric between the electrodes

“Volume” DBD

“Surface” DBD

“jet” DBD
Dielectric Barrier Discharges: different regimes

- Most commonly DBD develops into filaments crossing the whole gap
- under peculiar conditions: diffuse Townsend or even glow discharge

DBD geometry is a capacitance

Plasma “OFF”

DBD = capacitive limitation of the current

resistive limitation → Joule heating
Inductive limitation → current rise time limited
DBD geometry is a capacitance

Measure of power dissipated into the plasma

\[
P = 4f \cdot U_b C_{\text{die}} \left[ U_{\text{peak}} - \frac{C_{\text{die}} + C_{\text{gas}}}{C_{\text{die}}} \cdot U_b \right]
\]

\[
Q_{\text{cell}} = C_m V_m
\]

\[
Q = \int I(t)\,dt = CV
\]

Slope = \( C_{\text{die}} \)

Slope = \( C_{\text{cell}} \)
DBD geometry is a capacitance


Voltage across the gas gap remains constant at breakdown voltage

\[ I = I_{plasma} + I_{gas} \]

\[ V_{gas} = V_a - \frac{1}{C_{die}} \int I(t) dt \]
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DBDs: micro-discharge regime (filamentary mode)

- streamer growth

- Avalanches are leaving the cathode

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DBDs: micro-discharge regime (filamentary mode)

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- Avalanches are leaving the cathode

- space charge is formed at the anode

- “positive” streamer is growing

- charge deposition on the dielectric shield

Each filament = micro-chemical reactor

Species are diffusing accordingly to their life time

Modeling the chemistry of 1 filament:

- Need to take into account radial diffusion
- Calculation on time scale from 1 ns to 1h !!!
How to ignite another filaments?

a) At another place on the dielectric (field not shielded yet)

b) At the same place if the voltage is increased enough

c) at the same place by reversing the polarity

DBD is never powered by DC voltage

About micro-discharges in DBD...

✓ Development through positive streamer mechanism (~ 10 ns)

✓ Plasma column weakly ionized, similar to a transient high pressure glow discharge

✓ The dielectric is stopping the growth (need for periodic power supply)

• How are charges “adsorbed”?
• Are they only stopping the filament?
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Why a filament in a DBD is never starting in the middle of the gap?

Why is it developing most of the time through a positive streamer?
Role of adsorbed charges in pre-breadown phase?

Microdischarges development measured by Cross-Correlation Spectroscopy


Charge build-up in front of the anode (>200 ns!) before streamer starts (“pre-breakdown” phase)
Role of adsorbed charges in pre-breakdown phase?

Microdischarges development measured by Cross-Correlation Spectroscopy


- Charge build-up in front of the anode (>200 ns!) before streamer starts (“pre-breakdown” phase)
- Accumulation of many avalanches
- Avalanches become efficient only where the field is enhanced by the adsorbed charge
Role of the dielectric in filament ignition

How the dielectric is stopping the filament?
influence of the dielectric in filamentary DBDs

What happens when the streamer reach the dielectric?

$U_{\text{applied}} \approx 10^4 V$

$n_e = 3 \cdot 10^{13} \text{ cm}^{-3}$

$Q \approx 0.5 \text{nC}$

$C_d = \varepsilon_0 \varepsilon_r \frac{A}{d} \approx 10^{-3} \text{ pF}$

$U = \frac{Q}{C} \approx 10^6 V$!!!

The filament must spread over the dielectric
DBD: streamer spreading over the dielectric

What happens when the streamer reach the dielectric?


Electrography with red lead and lycopodium powder

A longer filament carries more charge

Larger spreading on the dielectric
What happens when the streamer reach the dielectric?

- The capacitance of the dielectric is driving the filament spreading
- higher capacitance, slower discharge

Role of permittivity of the dielectric material is different depending on the direction of E field with respect to the surface:

- E perpendicular: Charging of the capacitance make the discharge slowing down
- E parallel: desorption of charges and reinforcement of local field
  Adsorbed negative ions are desorbed and give back electron by detachment
DBD: streamer spreading over the dielectric

model for describing “n” filaments over the surface

Akishev et al, Plasma Sources Sci. Technol. 20 (2011) 024005

Streamer over a dielectric = resistor and capacitances in series

• About 1/3 of energy dissipated by a streamer, is dissipated over the dielectric surface
• A “volume” micro-discharge is also a “surface” one...
How charge is “adsorbed” on the dielectric?

- Electrons trapped in lattice default of the material with energy about 1eV
- Negative ions physisorbed? Chemisorbed?
- In any case γ is strongly enhanced by charges “adsorbed” on the dielectric

About micro-discharges in DBD...

- Adsorbed charges
- Stop the micro-discharges AND Initiate the micro-discharges

- “pre-breadown“ phase can be 0.1-1 µs!
- Adsorbed charges are e- trapped, or negative ions?
- Charges adsorption energy is weak (~ 1 eV)
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Self organization: field shielding


- Adsorbed charge fix the position of the filaments
- Distance between filaments depends on spreading

Low voltage

Picture integrated in time

• Adsorbed charge fix the position of the filaments
• Distance between filaments depends on spreading
Self organization: gas phase contribution

2nd filament unstable

Instability of 2nd filament: gas phase vs surface

Field is higher between the 1st filaments
But
Gas is “pre-excited” close to 1st filaments

Behavior of a DBD is driven by this question:
Where will occur the most efficient avalanches?

Surface charges distribution

Vs

SHIELD the field during the same half-period

Provide first e- when polarity is reversed

diffusion of excited species in the gas phase

Equations for describing such system:
activator-inhibitor equations

\[
\frac{da}{dt} = \frac{pa^2}{h} - \mu a + D_a \frac{d^2 a}{dx^2}
\]

\[
\frac{dh}{dt} = p'a^2 - \nu h + D_h \frac{d^2 h}{dx^2}
\]

About filaments interactions

✓ Filaments can be self-synchronized and/or spatially organized

✓ Filaments can interact through:
  - field of the streamer itself
  - emitted light
  - field shielding
  - excited species diffusion

How the surface and gas phase contribution can lead to diffuse discharge?
How to get a diffuse discharge at atmospheric pressure?

1) e⁻ emission from the surface over a large area
How to get a diffuse discharge at atmospheric pressure?

1) e- emission from the surface over a large area
   a) Increasing $\gamma_{\text{eff}}$

Adsorbed aceton release e$^-$ in Ar discharge

High $\gamma$ material: Al$_2$O$_3$, MgO

Warning: it is an effective $\gamma$ that include desorption of electron...
How to get a diffuse discharge at atmospheric pressure?

1) e- emission from the surface over a large area
   a) Increasing $\gamma$
   b) lower surface resistivity

- Use of semi-conductor as “barrier”
- similar idea with discharges above water surface


M. Laroussi et. al., 2002 Int. Power Modulator Conf
How to get a diffuse discharge at atmospheric pressure?

1) e- emission from the surface over a large area
   a) Increasing $\gamma$
   b) lower surface resistivity
   c) High flux of energetic particles to enhance $\gamma_{\text{eff}}$
      (ions, metastables...)


ex: Diffuse Townsend $N_2$ discharge:
secondary electron emission from metastable $N_2(A^3\Sigma_u)$ impact
Admixture of $O_2$ quenches $N_2(A^3\Sigma_u)$ (+ attachment)
diffuse discharge: gas phase conditions

How to get a diffuse discharge at atmospheric pressure?

1) e- emission from the surface over a large area

2) gas phase homogenisation
   a) Very short gap


Townsend discharge in air inside polymer voids

Important topic for plasma/catalyst coupling and insulator damaging
diffuse discharge: gas phase conditions

How to get a diffuse discharge at atmospheric pressure?

1) e- emission from the surface over a large area

2) gas phase homogenisation
   a) Very short gap
   b) Pre-ionize the gas

Numerous simultaneous avalanches

Require pre-ionization with \( n_e^0 \approx 10^6 \, cm^{-3} \)

Example: photo-triggered discharge

How to get a diffuse discharge at atmospheric pressure?

1) e- emission from the surface over a large area

2) gas phase homogenisation
   a) Very short gap
   b) Pre-ionize the gas
   c) Multi-steps ionization
   d) diffusion of excited species

Ionization of excited species having life time long enough to diffuse “self-pre-excitation” of the gas

\[ e^- + A \rightarrow A^* + e^- \]
\[ A^* + B \rightarrow B^+ + e^- \]

Examples:
- penning ionization in Ar/NH$_3$
- ionization of He metastables

**DBD: homogeneous discharges**

**In Nitrogen:**
- High $\gamma$
- Increased by metastable $N_2(A^3\Sigma_u)$ impact
  - Surface emission favorable


**In Helium:**
- $\alpha$ slowly varying with E field
- 2 steps ionization (metastables over large volume)
- Penning ionization if impurities
  - Surface AND gas phase favorable


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O. Guaitella – DBDs and Coronas
About filaments interactions

diffuse DBD discharge can be obtained at atmospheric pressure with:

✓ Enhanced electron emission from the surface
✓ pre-excited species over the whole gas volume
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Gas motion induced by filaments: ion wind

Using plasma for limiting turbulences

Corke et al, Exp Fluids 46 (2009) 1–26
Gas motion induced by filaments: ion wind

The force per unit volume transmitted by positive ions to the neutral molecules = ion momentum loss per unit volume per unit time

\[ f_i = m_i n_i v_{im} v_i = \frac{m_i v_{im}}{e} e n_i v_i = \frac{j_i}{\mu_i} \]

The same for electrons

\[ f_e = \frac{j_e}{\mu_e} \]

The total force

\[ f = \frac{j_i}{\mu_i} - \frac{j_e}{\mu_e} = e(n_i - n_e)E - kT_i \nabla n_i - kT_e \nabla n_e \]

The force is important only in non neutral zone

• Capillary discharges in noble gases: “overflowding” of an homogeneous discharge!

• plasma bullet propagation is possible because of confinement of charges

• it is slowed down by the capacitance of the tube

• when it exit in the surrounding atmosphere it is following the flow of He

A Sobota, Plasma Sources Sci. Technol. 23 (2014) 025016
Basic plasma parameters can be measured -> begining of good comparison with models

Electric field measurements in a kHz-driven He jet - the influence of the gas flow speed, A Sobota et al, Plasma Sources Science and Technology (2016) accepted
DBD Plasma jet in kHz range: a model ionization wave

Model for ionisation waves interaction with surfaces

E Slikboer, O Guaitella, A Sobota
Plasma Sources Science and Technology 25 (3), 03LT04
DBDs and Corona develop different discharges

Building up of a localized space charge determine the discharge behavior

Balance between charge adsorption/emission from the surface and remaining excited species in gas phase is essential for DBD

Chemistry very complex but also very efficient
Books

- Yu. P. Raizer « Gas Discharge Physics » (Springer)


- J. Reece Roth « Industrial Plasma Engineering » (IOP)- Nato ASI Series
  “Electrical breakdown and discharges in gases:
  “Non Thermal Plasma Technologies for Pollution Control” 1993

- Ch. K. Rhodes « Excimer Lasers » (Springer-Verlag)


Filamentary discharges at atmospheric pressure

Lighting: surface interaction for regular breakdown and salt evaporation

Electrostatic precipitation and flow control: ion wind

large variety of research topics!!

Assisted combustion and air treatment:
Breadown in voids and high pressure complex chemistry

Biomedical applications:
Heating processes, complex chemistry, surface interaction

Surface reactivity