icpm 11 &

Summer School of 11th International Conference on Plasma Medicine
May 31, 2026, Gifu, Japan

Fundamentals of Atmospheric Plasmas

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Summer School Lectures

13.00 Joao Santos Sousa – Plasma devices for plasma medicine and agriculture

13.45 Laura Fouassier – Plasma for cancer treatment

14.45 Thomas von Woedtke – Plasma medical applications

15.30 Kazunori Koga – Plasma agricultural applications

16.30 Nagendra Kaushik – Plasma-cell and plasma-tissue interactions

17.15 **Karol Hensel** – **Fundamentals of atmospheric plasma**

18.15 Pepijn Heirman – Modeling

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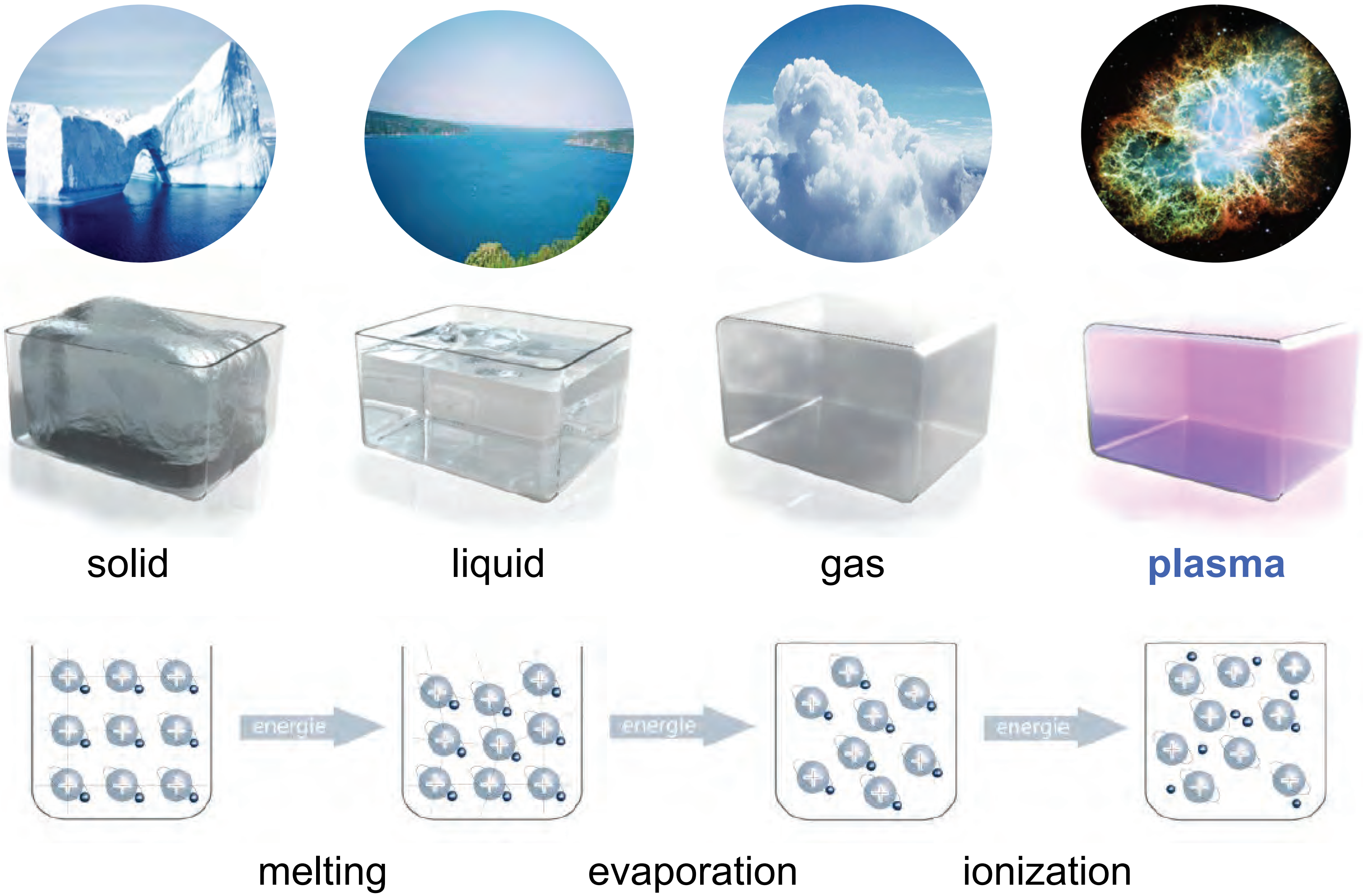
What Is Plasma?

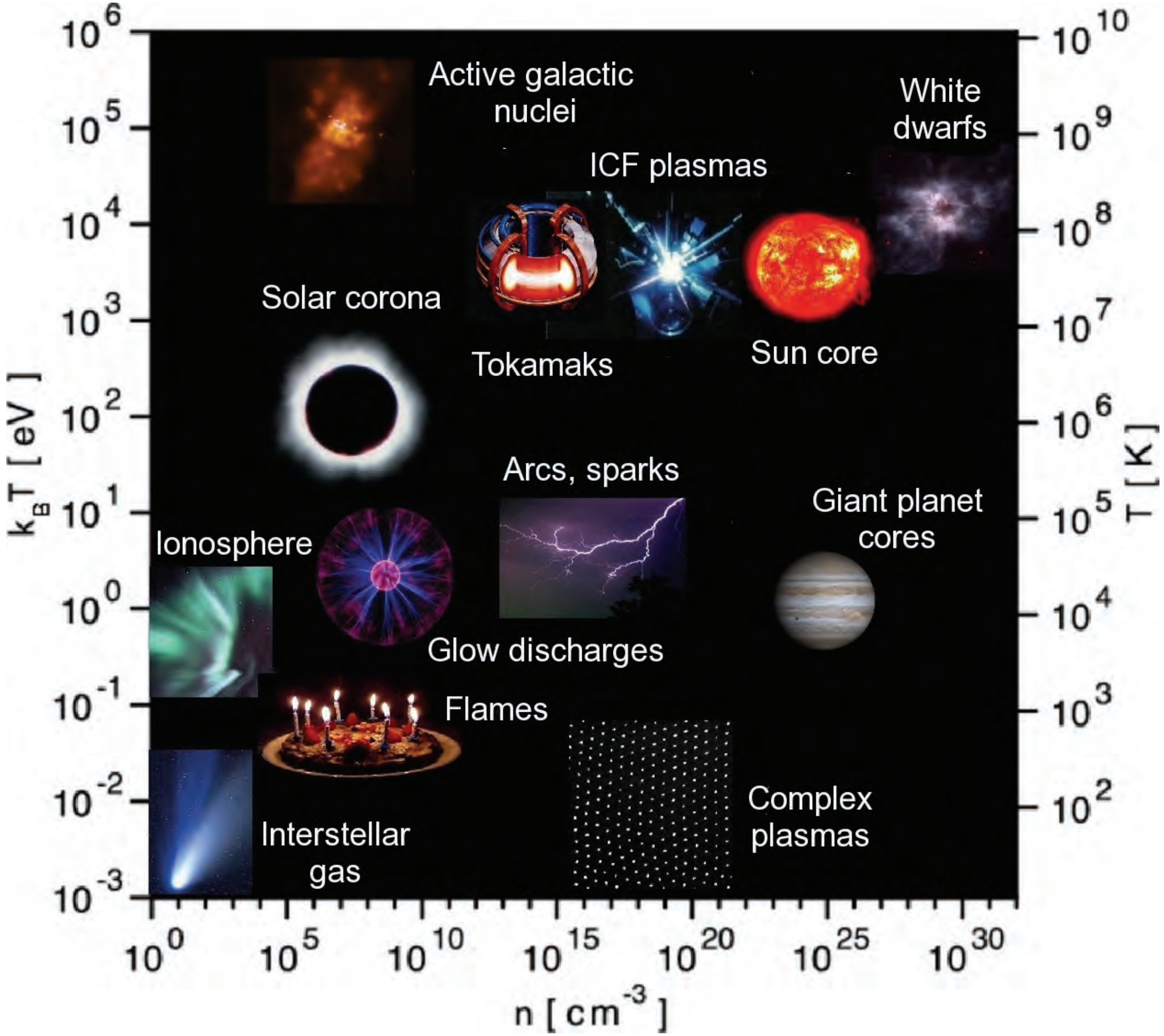


temperature (energy)

Irving Langmuir (US)

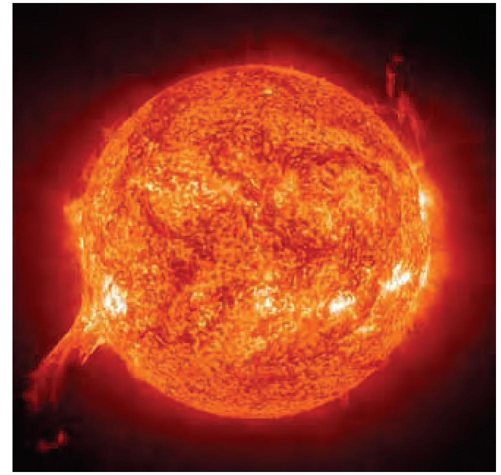
He first used the term **plasma** by analogy with the blood plasma as transport of electrons reminded him of the way blood plasma carries red/white cells

Plasmas in Nature



temperature vs density of charged particles

Universe



Sun

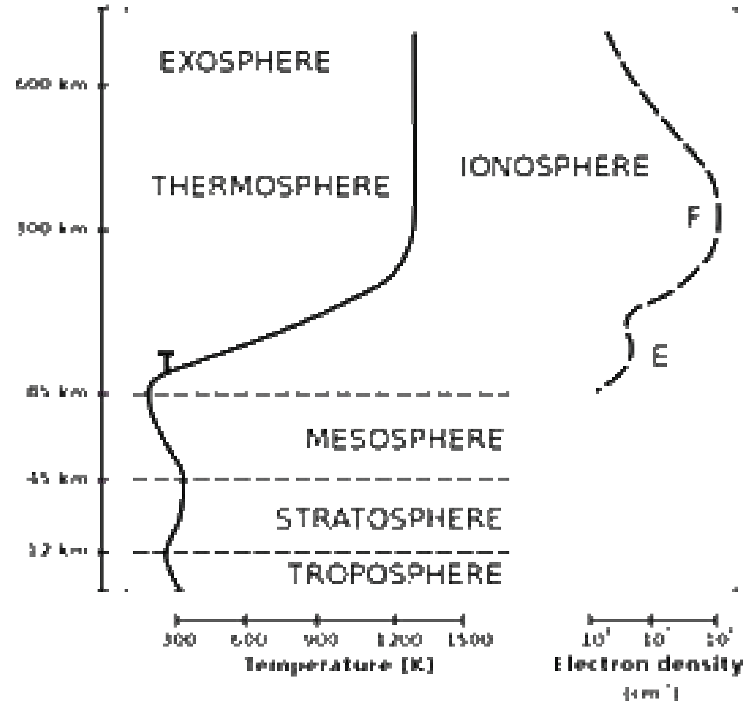
fire

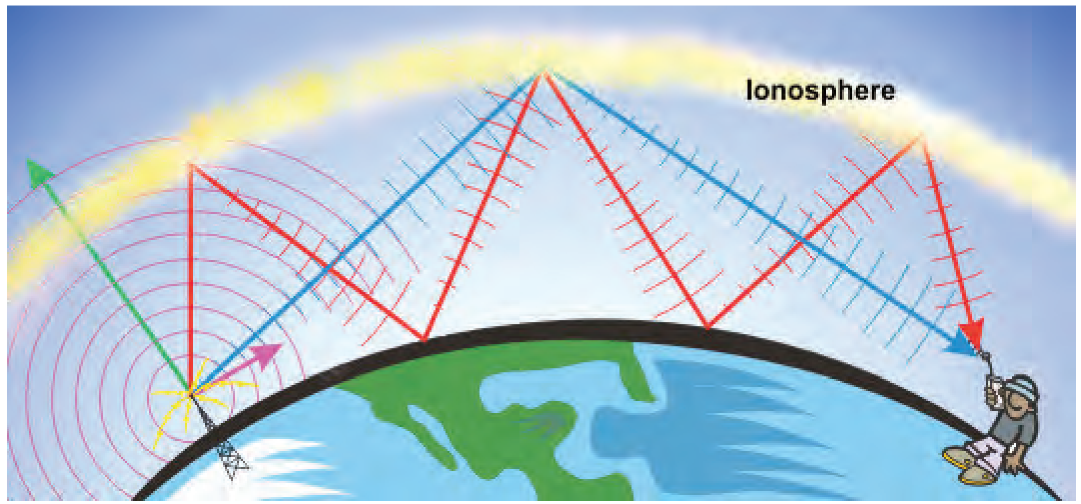
Plasmas in Nature

lightning

aurora (northern lights)

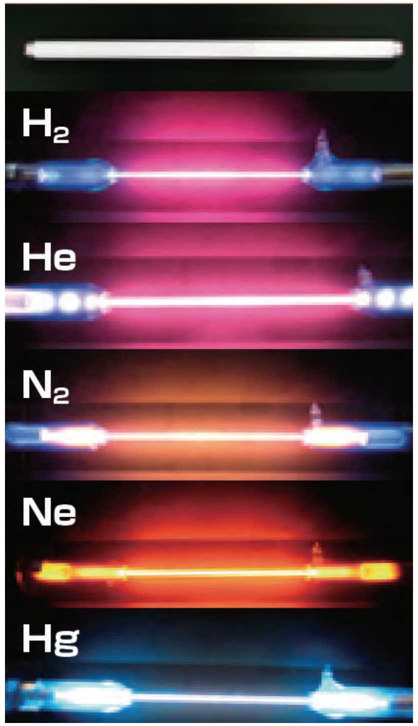
ionosphere





Plasmas Generated by Humans

fluorescent lights

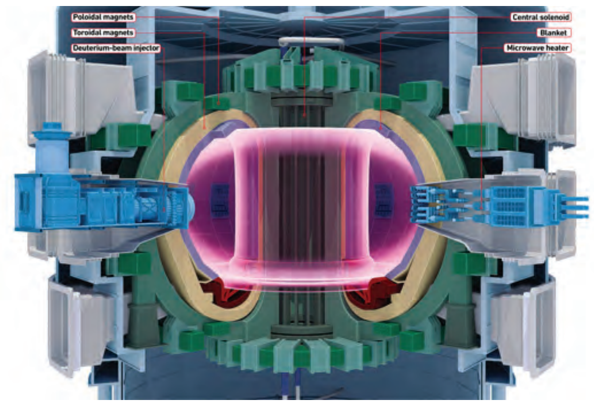


smoke detectors

welding

plasma TV

copiers

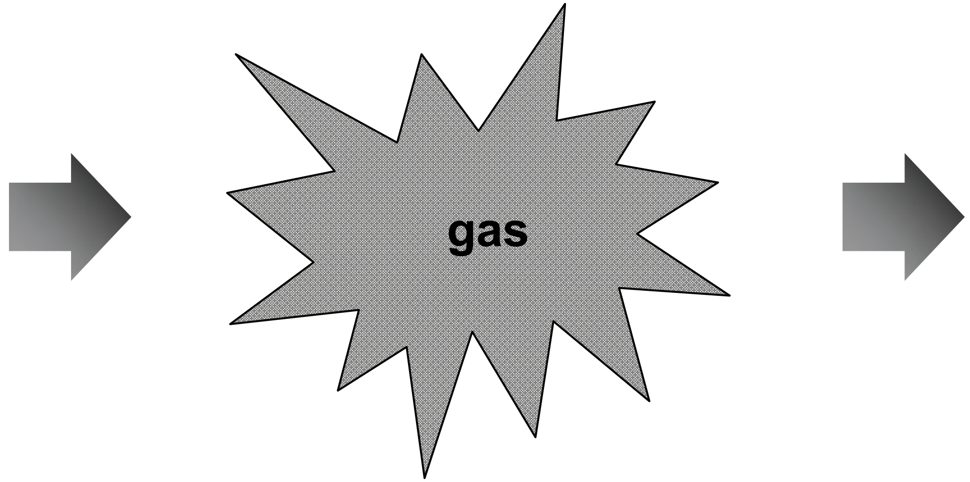


fusion plasma

Generation of Plasma

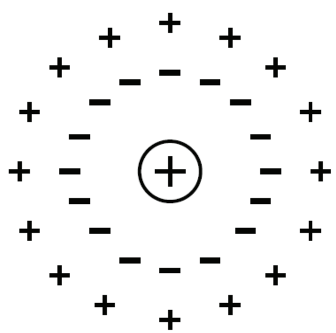
- To produce plasma, it is necessary to liberate electrons that are normally bound in atoms/molecules.

source of energy
heat
pressure
EM fields
particles
laser
chemical reaction



electrons
ions
excited particles
radicals
photons

- Gas containing ions and free electrons is called **ionized gas**. Under special circumstances, it can be **plasma**. Plasma is a collection of neutral and charged particles, but it must satisfy criteria → **Debye–Hückel theory**



$$\varphi(r) = \frac{q}{4\pi\varepsilon_0 r}\exp\left(-\frac{r}{D}\right)$$

→ charges arrange themselves to shield out the electric field of a test charge

$$\boxed{D = \sqrt{\frac{\varepsilon_0 k T}{2e^2 n_0}}}$$

→ **Debye length** = distance (D), at which the field of single charged particle is effectively shielded

k = Boltzman constant
T_- = electron temperature [K]
n_o = electron concentration [cm^{-3}]

Peter Debye (NL, US)

Types of Plasma

- Criterion for the plasma existence:
  1) linear dimension of the plasma (L): $L >> D$
  2) quasi-neutrality must be fulfilled: $n_i \approx n_e$

$$N_D = \frac{4\pi}{3} D^3 n_0 \geq 1$$

shielding can be effective only
if the number of charged particles $N_D > 1$

- Basic characteristics of plasma: concentration (n_g, n_e, n_i) and temperature (T_g, T_e and T_i) of particles.
- Types of plasma:
  - by density of charged particles: weakly ionized ($n_g >> n_e, n_i$) or strongly ionized ($n_g < n_e, n_i$) plasma
  - by temperature: high temperature ($T > 10^6$ K) or low temperature ($T < 10^6$ K) plasma
  - by temperature: or thermal ($T_e \approx T_g \approx T_i$), or non-thermal ($T_e >> T_g, T_i$) plasma

thermal
(high temperature/equilibrium)
ionization by atoms and molecules
$T_g \approx T_i \approx T_e > 10^5$ K

↓

Sun, stars, fusion plasma, lightning

non-thermal
(low temperature/non-equilibrium)
ionization by electrons
$T_i \approx T_g \approx 300\text{-}400$ K
$T_i << T_e \sim 10^4\text{-}10^5$ K (1-10 eV)

↓

ionosphere, **electric discharges**

Generation of Non-Thermal Plasma

- Electrons are key factor in plasma chemistry → electron impact on atoms/molecules of background gas.

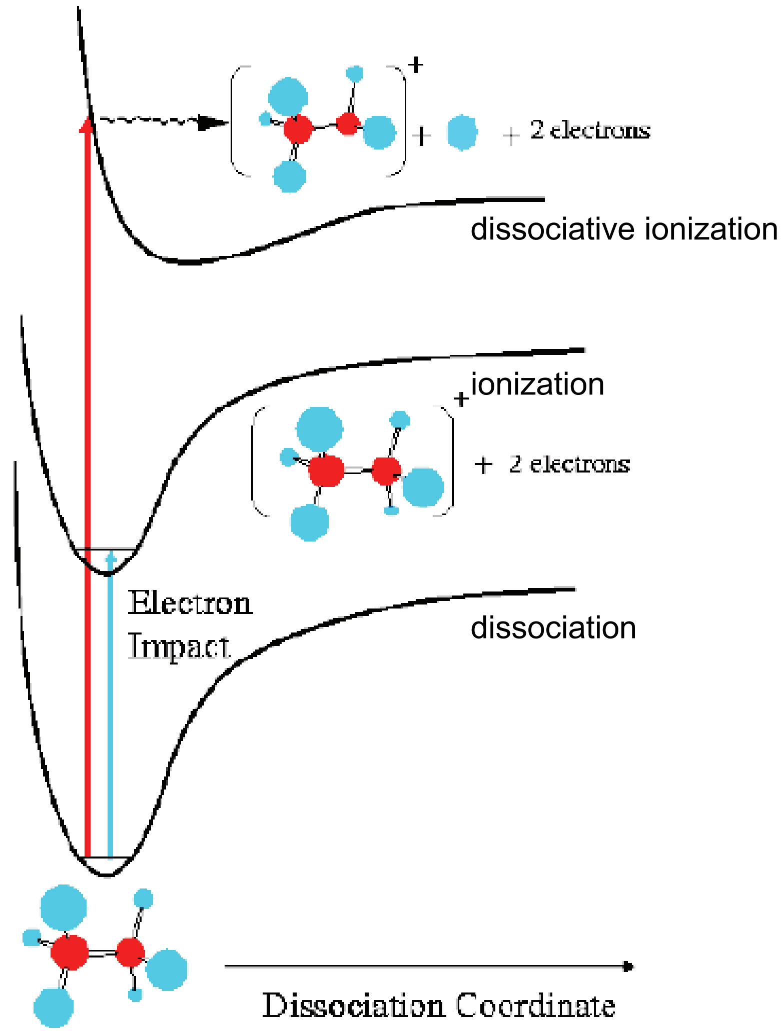
  e + M → M + e (elastic scattering)
  e + M → M* + e (excitation: rotational, vibrational, electronic)
  e + M → M^+ + 2e (ionization)
  e + M → M^- (electron attachment)
  e + AB → A + B + e (dissociation)
  e + AB → A^+ + B + 2e (dissociative ionization)
  e + AB → A^- + B (dissociative electron attachment)

- The probability of the processes depends on their **threshold energy** and **cross-section** (σ).
- Electron energy E_e gained from electric fields: $\frac{1}{2}mv_d^2 = e.V$
- Distance between two collisions is called **mean free path** (λ).

$$\lambda = 1/(n_g.\sigma)$$

v_d = drift velocity
n_g = concentration of neutrals
σ = cross-section of each atom ($\sigma = \pi r^2$)

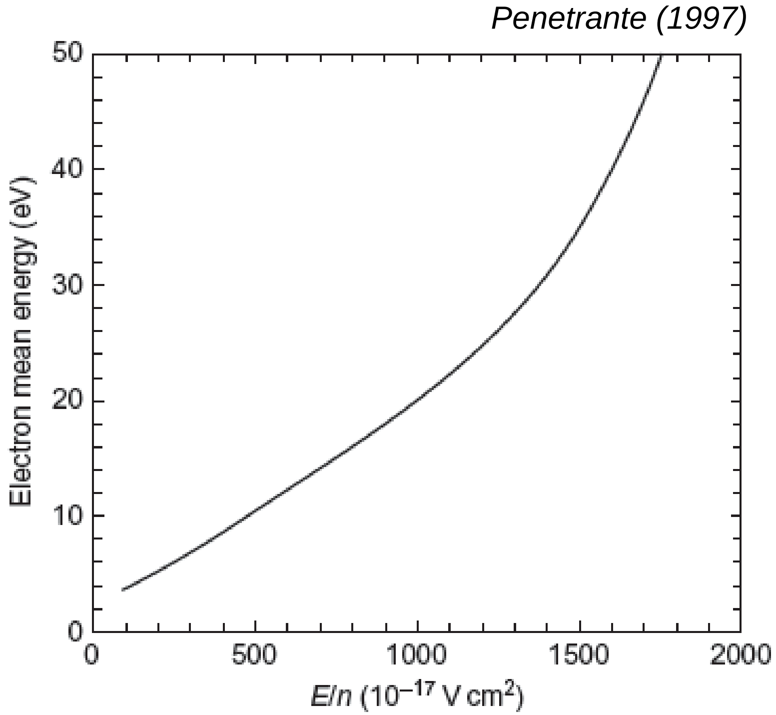
- Typical values: $\lambda_{atm} \sim 10^{-6}$ m
  $\sigma \sim 10^{-20}$ m$^2 \sim f(E_e)$
  $E_e \sim$ 1-10 eV



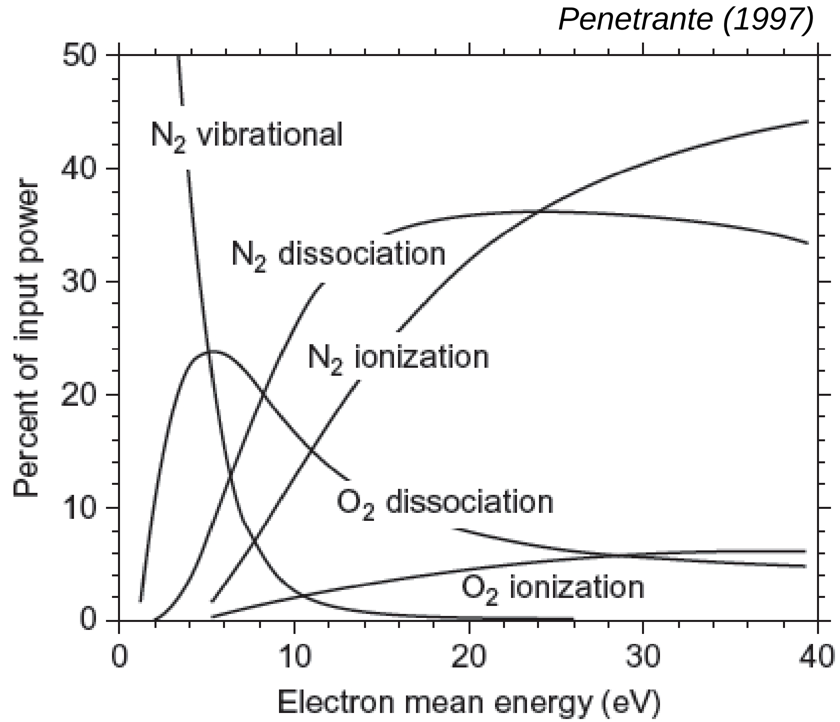
- Reality: calculation of λ, E_e requires a knowledge of a distribution function of electron velocities (EEDF).

Generation of Non-Thermal Plasma

- Parameter used to characterize the electron energy distribution function (EEDF) is the **electron mean energy**.



E_e vs. reduced electric field



power dissipation vs. E_e

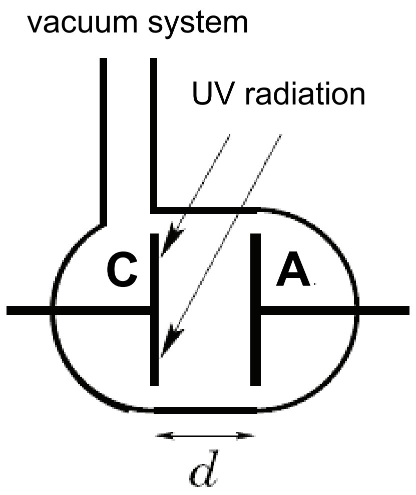
Bond	Energy (eV)
H–H	4.36
C–C	3.48
N–N	1.70
O–O	1.45
C–I	2.16
C–N	3.08
H–C	4.13
H–N	3.91
H–O	3.66
C=C	6.14
O=O	4.98
C–O	3.6

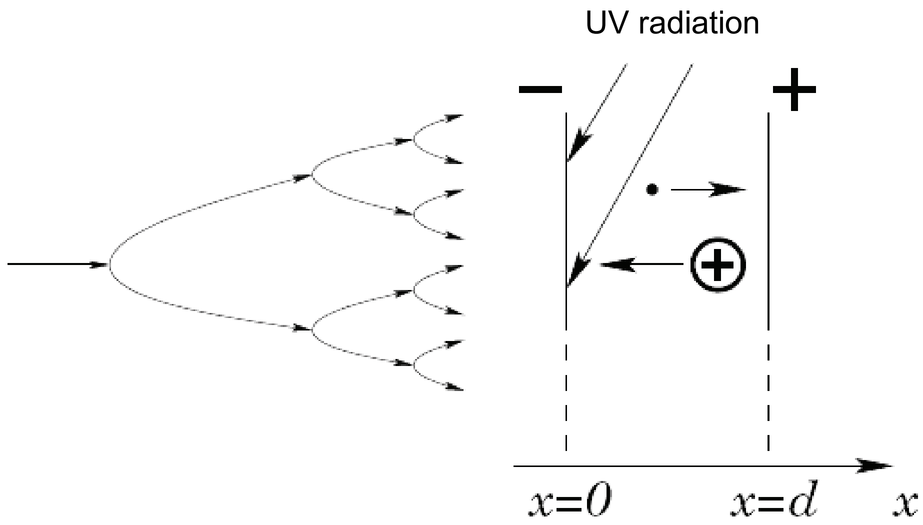
bond energies

$O_2 \rightarrow 2O$	5.16
$H_2O \rightarrow OH + H$	5.17
$CO_2 \rightarrow CO + O$	5.52
$NO \rightarrow N + O$	6.55
$N_2 \rightarrow 2N$	9.80
$CO \rightarrow O + C$	11.16

- The energies with electron mean energizer in a range of 1-10 V range can be easily generated by electric discharge at atmospheric pressure

Discharge Ignition and Breakdown in Gases

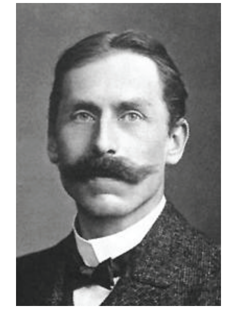




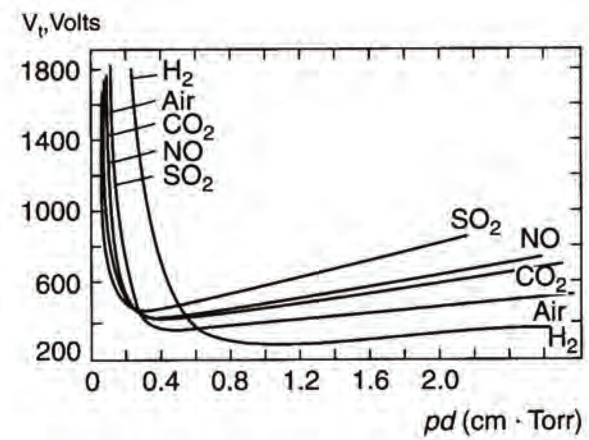
Paschen's law

$$U_z = \frac{B p_0 d}{\ln(A p_0 d) - \ln[\ln(1 + 1/\gamma)]}$$

p_0 = gas pressure
d = distance between electrodes
A, B = constants (for a given gas)



Frederick Paschnen (DE)



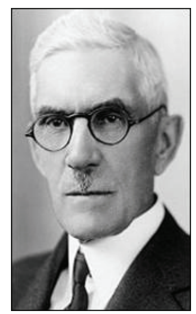
current density

$$i = \frac{i_0 \exp(\delta d)}{1 - \gamma[\exp(\delta d) - 1]}$$

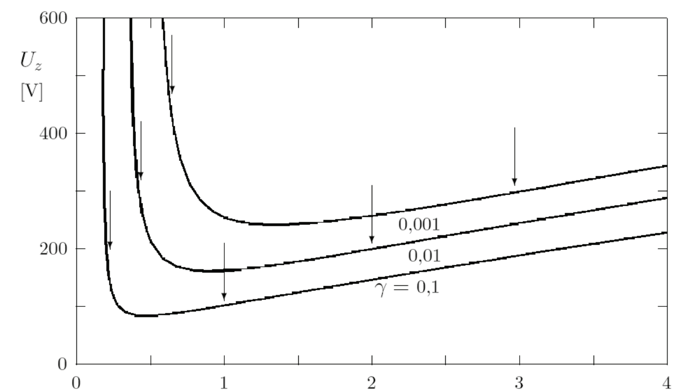
i_o = primary electron current density
d = distance between electrodes
δ = 1st Townsend (primary ionization) coefficient [m^{-1}]
(e produced by e-collisions in the electric field)
γ = 2nd Townsend (secondary ionization) coefficient
(e released from the C by ion, photon, or metastable)

$$\gamma[\exp(\delta d) - 1] = 1$$

Townsend criteria of breakdown in homogenous electric field

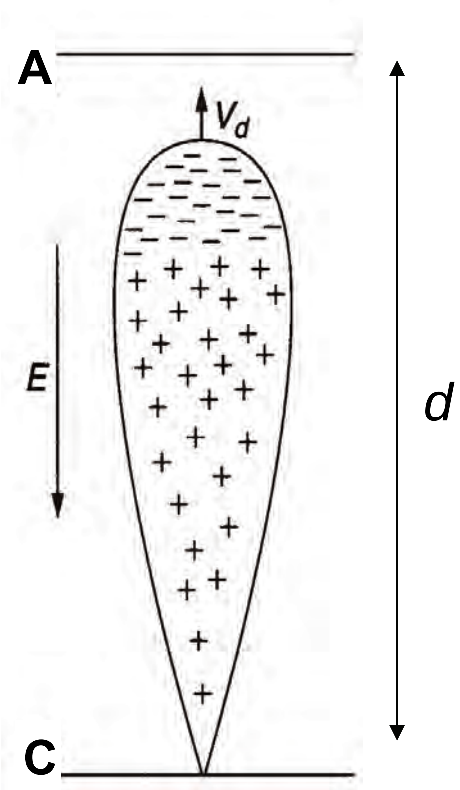


Francis Townsend (US)

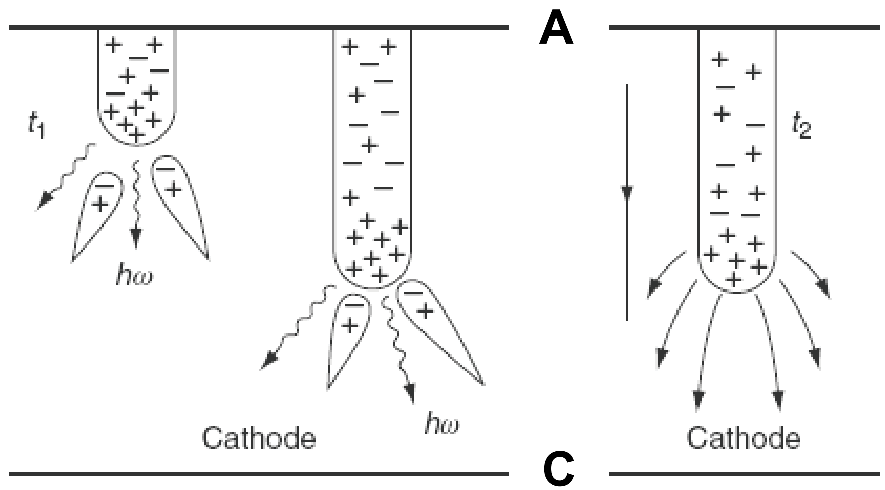


Breakdown in Gases – Streamer Theory

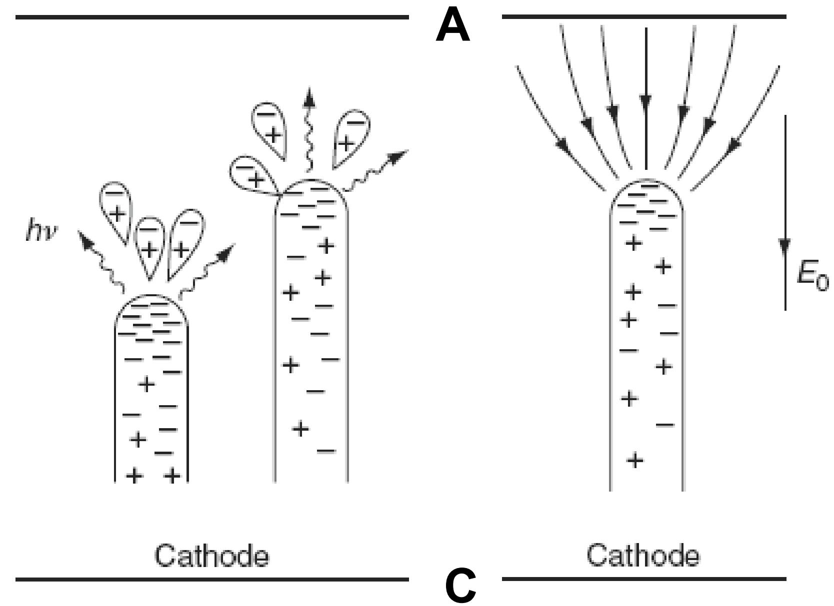
- Streamers is a breakdown in a gas when a strong electric field is applied.



Electron avalanche



Propagation of positive streamer with secondary avalanches



- **Meek's criterion** (M_k) - defines the critical threshold (Mk) at which electron avalanche transit into a self-sustaining streamer.

$$\boxed{M_k \approx \delta(E/n).d \approx 18-20}$$

$$N_e \approx \exp(\delta d) \approx 3\times10^8$$

number of electrons in an avalanche

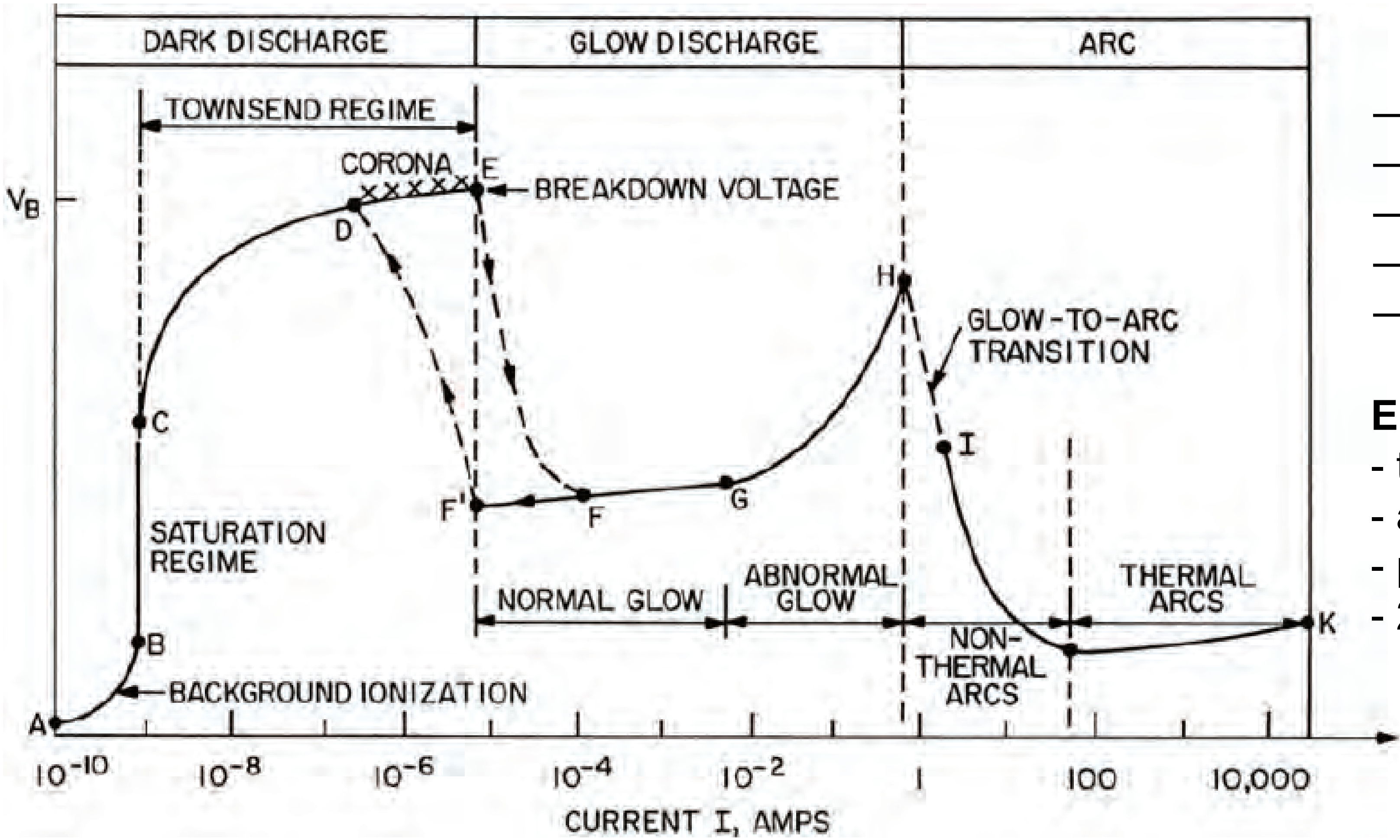
δ = Townsend ionisation coefficient
E/N = reduced electric field
d = distance between electrodes

- **Typical values:**

diameter ~ 0.1-1 mm
velocity ~ 10^7-10^9 cm/s
n_e ~ 10^{14} cm^{-3} (10^{19} m^{-3})

Electric Discharges

- **Electric discharge** = phenomenon that occurs after the breakdown between the electrodes. Nature of discharge depends on the pressure, geometry, gas composition, power source, etc.



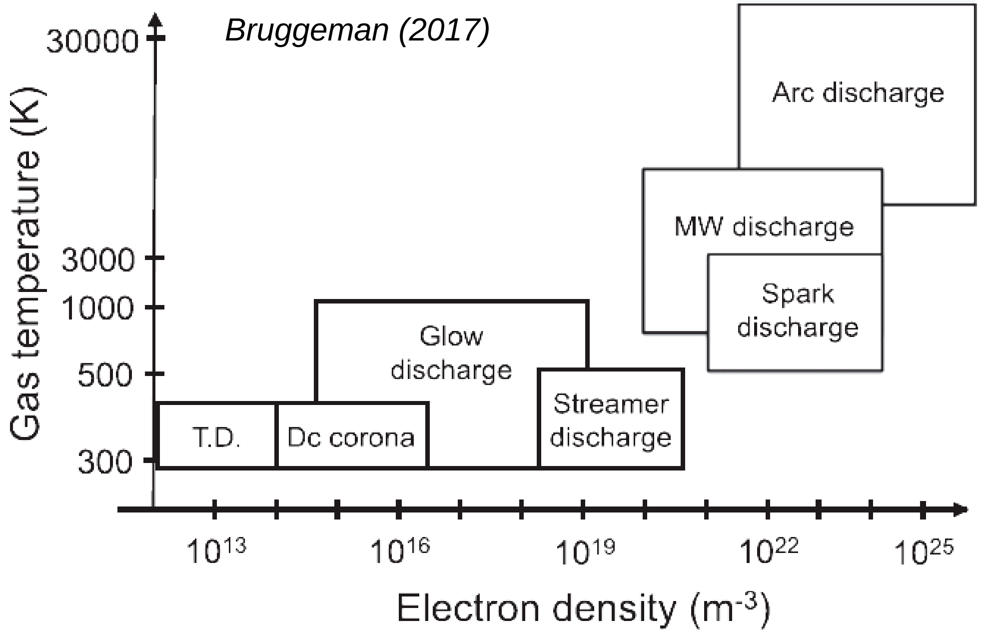
voltage-current characteristics of electric discharges

→ cosmic radiation
→ electron avalanche
→ Townsend (non-self-sustained)
→ corona (self-sustained)
→ glow/arc discharge

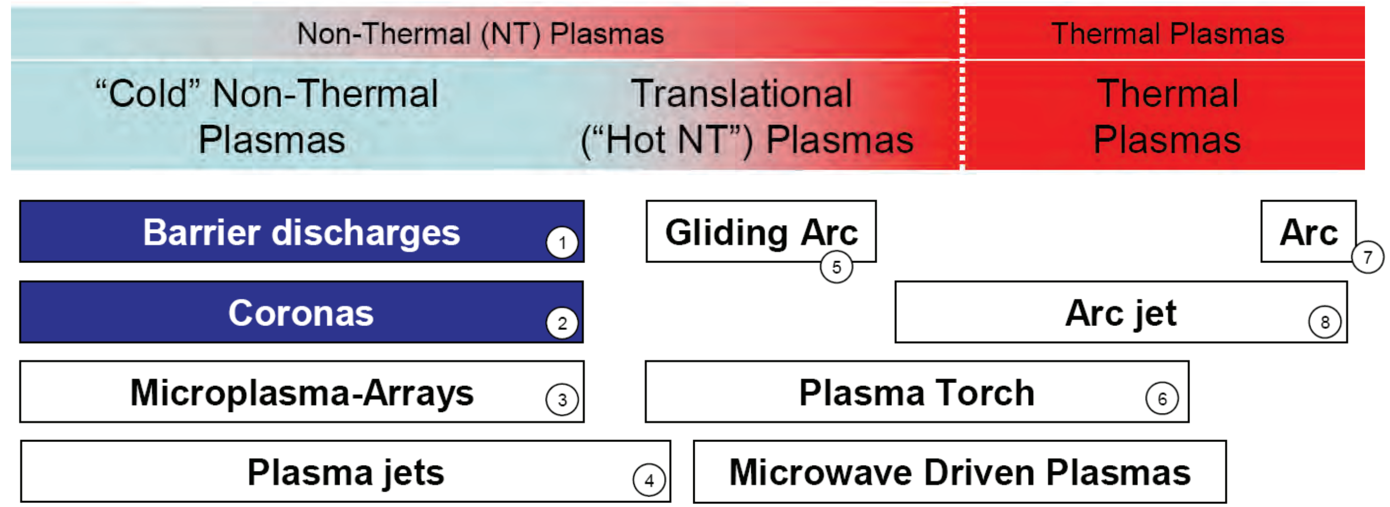
Electrons emission from metals:
- thermo-emission (by heat)
- auto-emission (by electric field)
- photo-emission (by photon)
- 2ndary-emission (by electrons/ions)

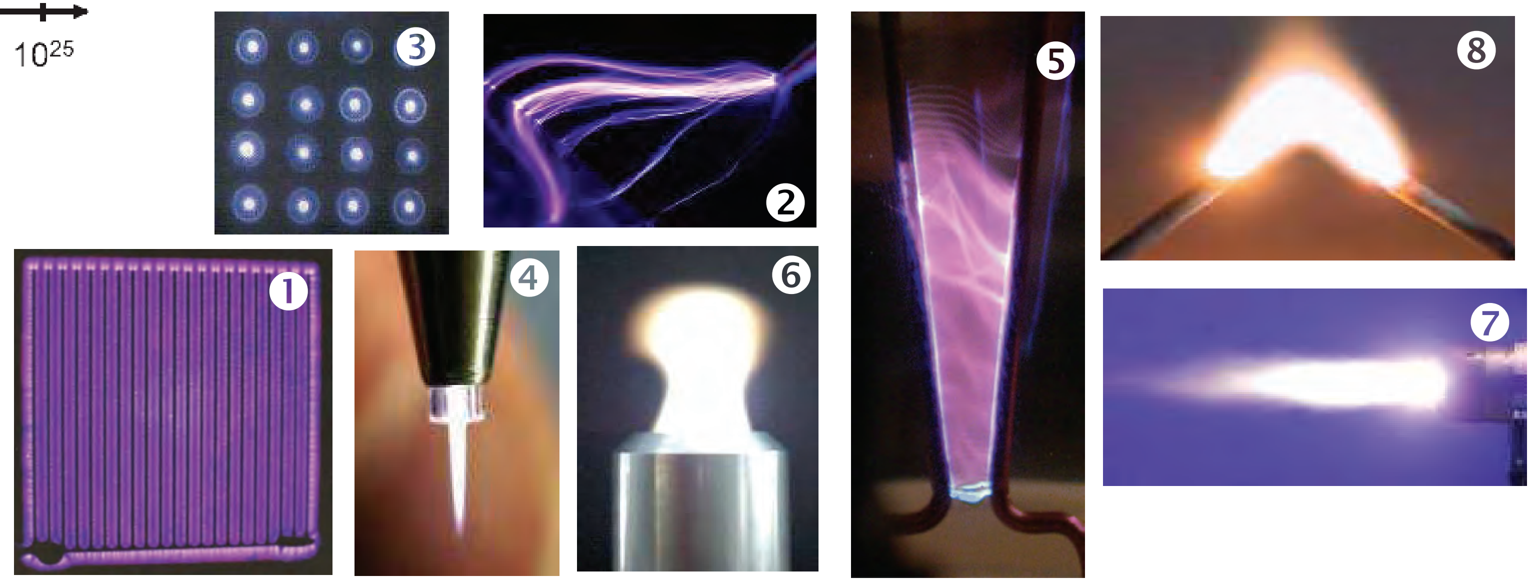
Atmospheric Electric Discharges

- **Electric discharge** = phenomenon that occurs after the breakdown between the electrodes. Nature of discharge depends on the pressure, geometry, gas composition, power source, etc.



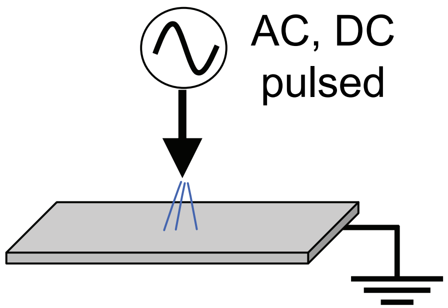
Atmospheric pressure discharges vs. T_g and n_e

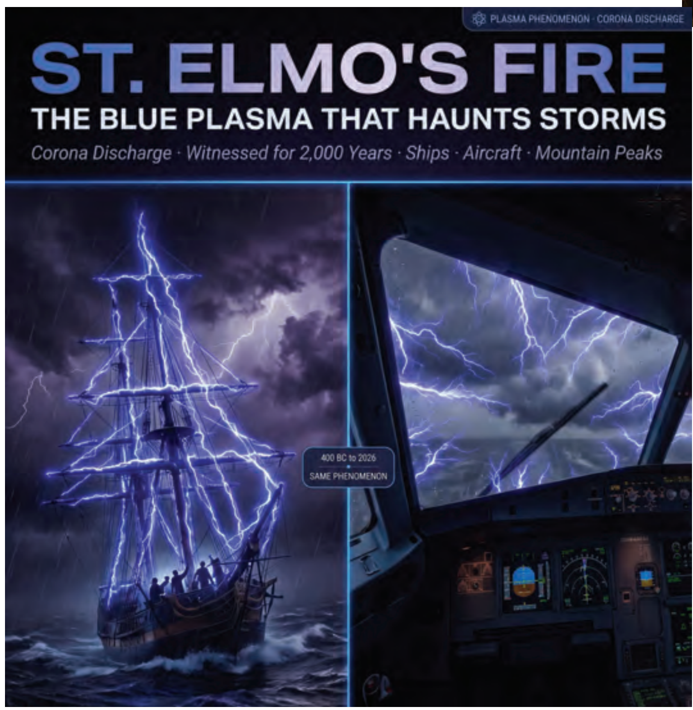


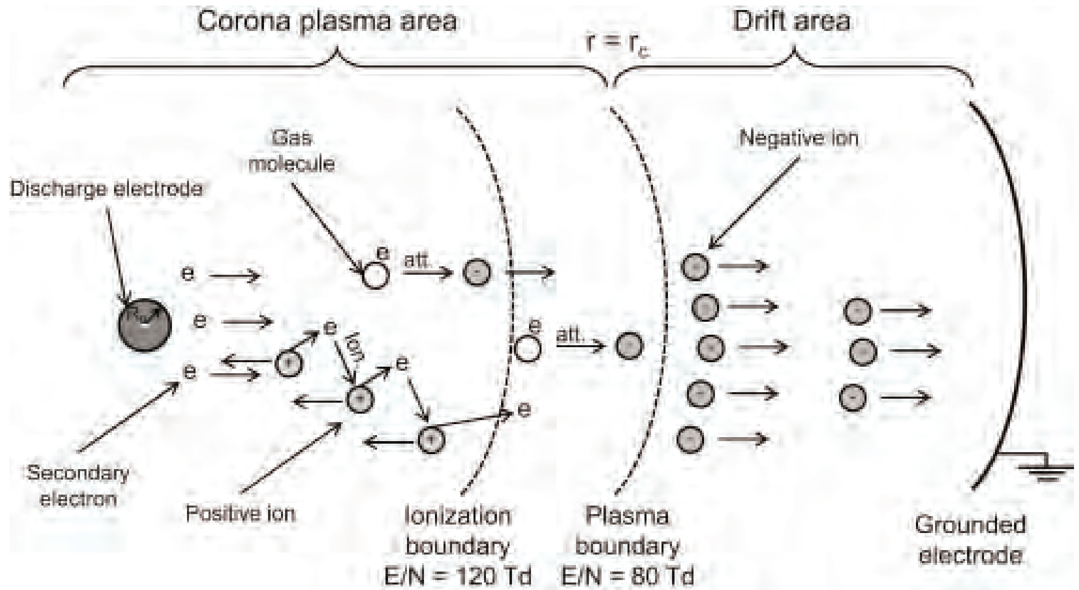


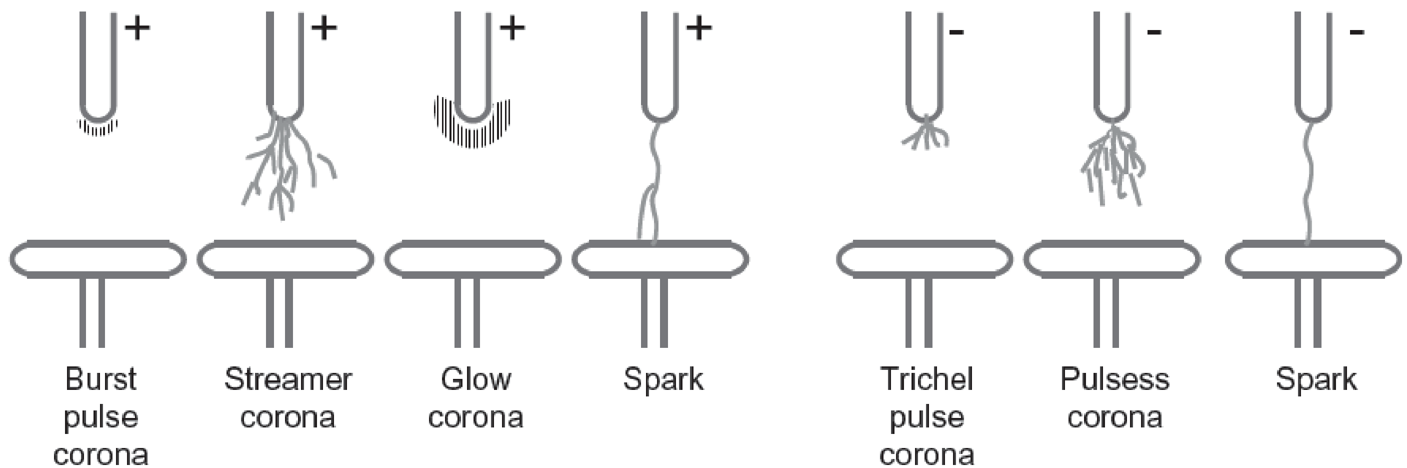
Atmospheric Discharges – Corona Discharges

- **Corona discharge** = discharge generated around wires, and sharp points/edges (in non-homogenous e-field)



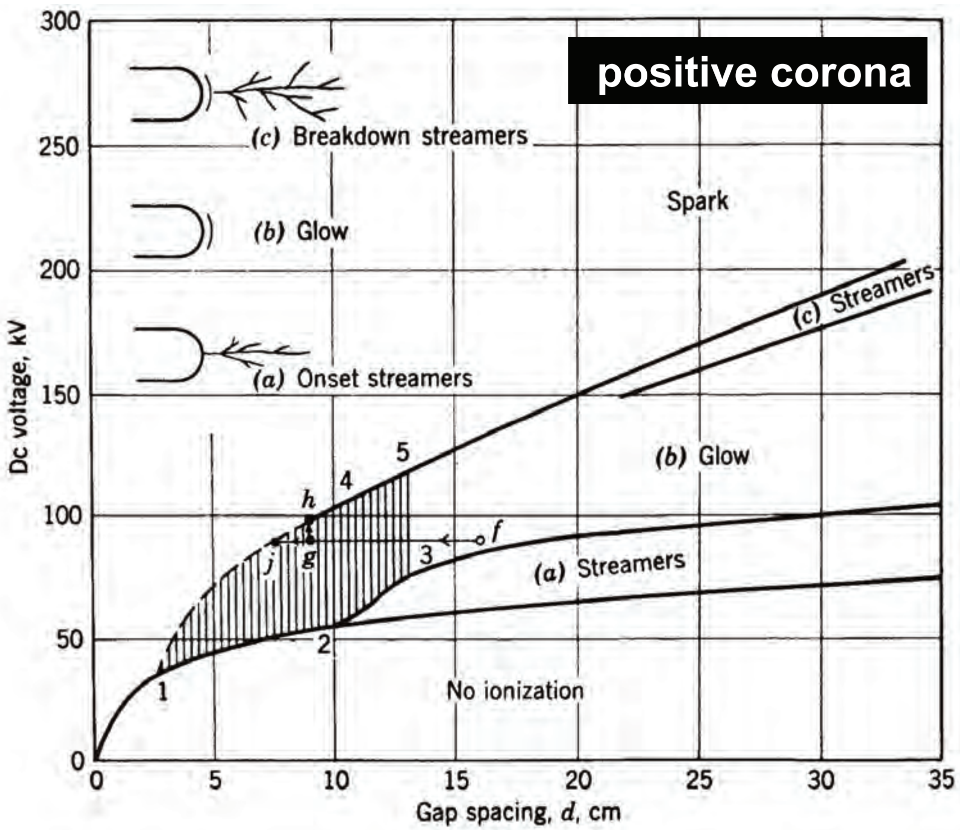






Corona discharge modes in positive and negative polarity

Atmospheric Discharges – Corona Discharges



Positive corona discharge modes vs. discharge gap

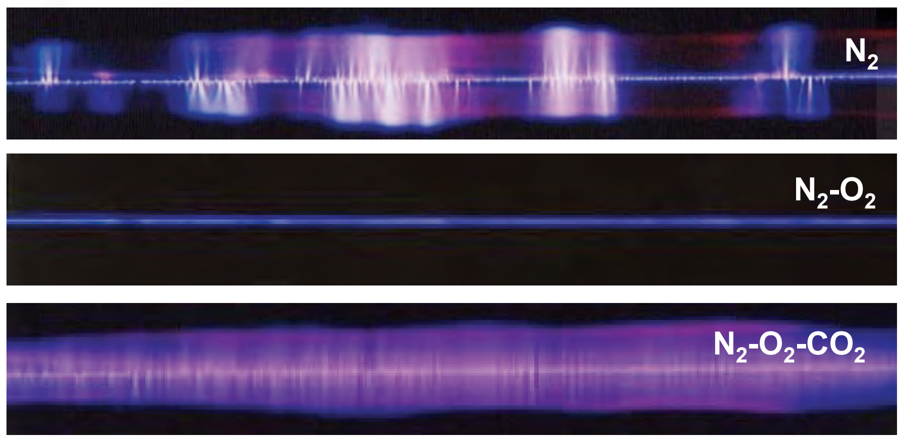
Corona discharge current

$$I = \frac{8\pi\pi_0 \mu V\left(V - V_0\right)}{R^2 \ln\left(R/r\right)}$$

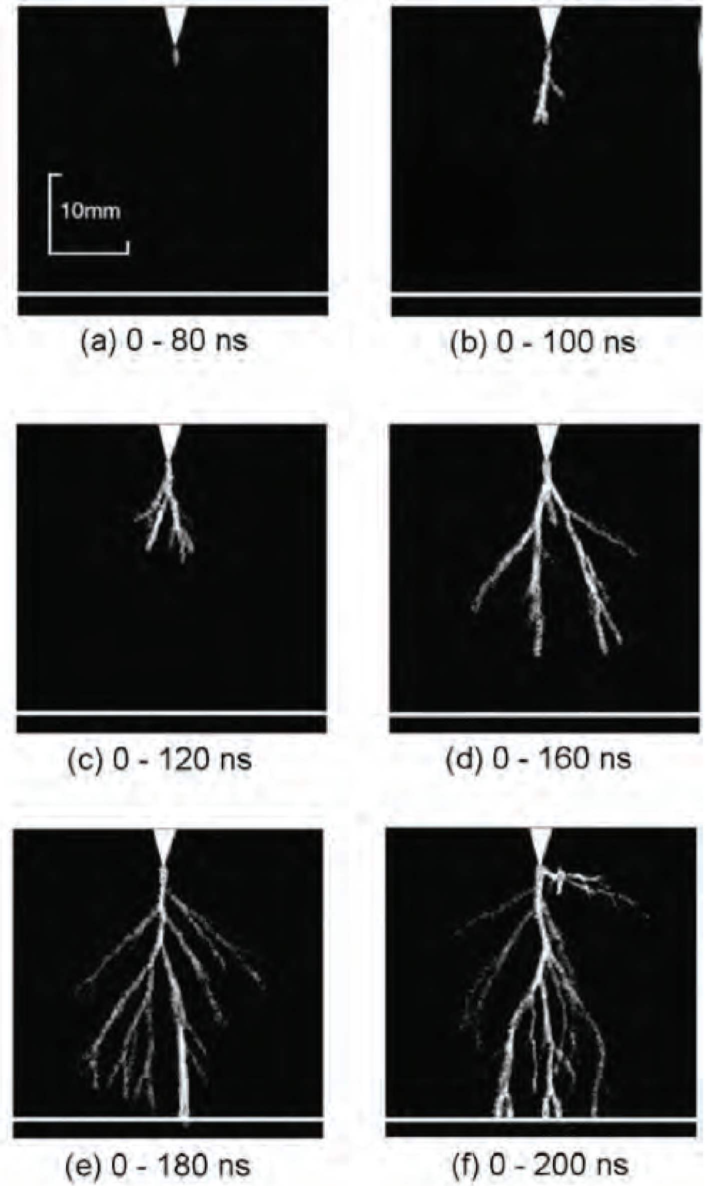
$$\downarrow$$

$$I = cV\left(V - V_0\right)$$

I = discharge current
c = constant (depends on geometry)
V = applied voltage
V_0 = inception (threshold) voltage
R/r = diameter of electrodes

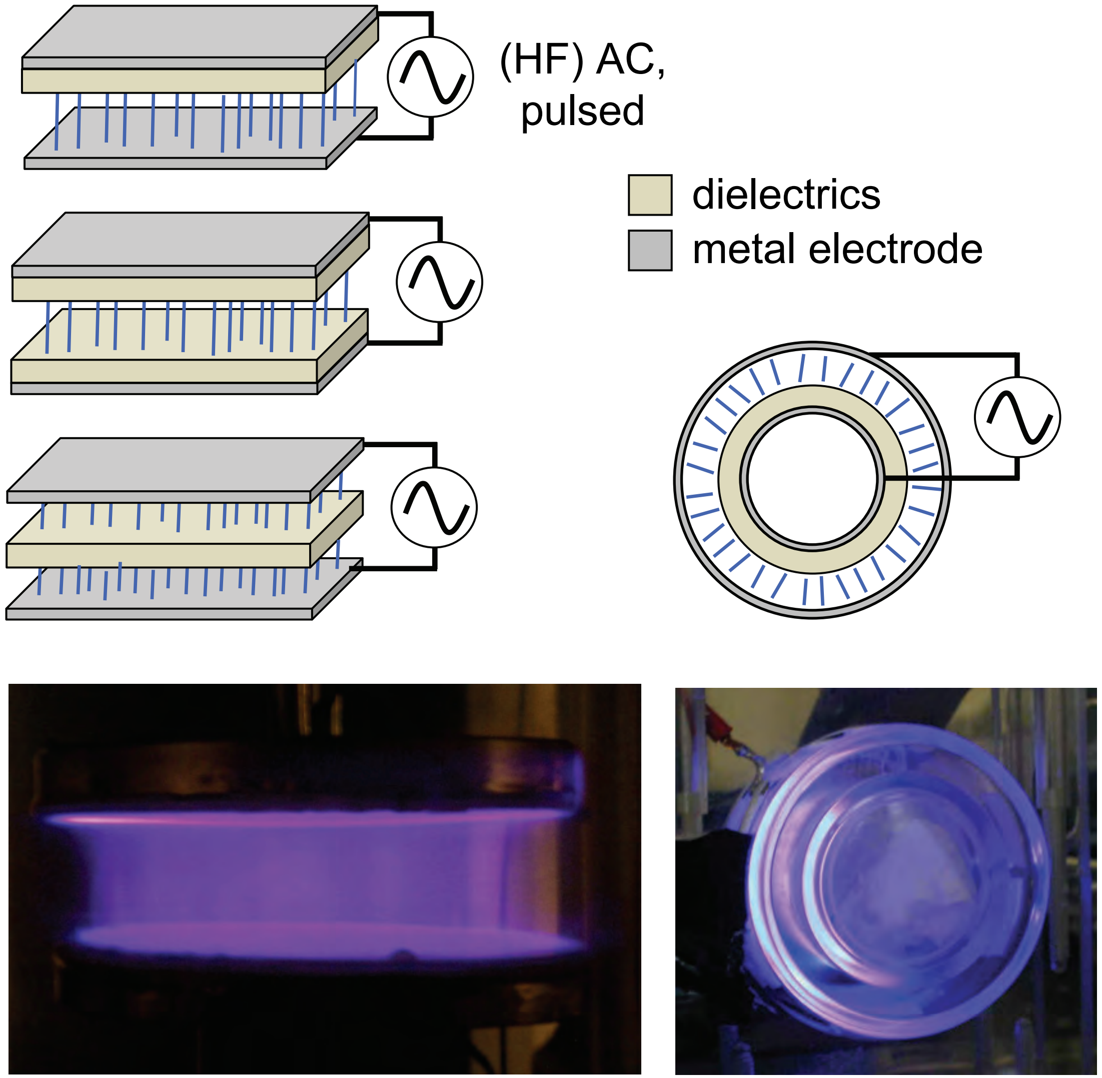


Mizeraczyk (2004)

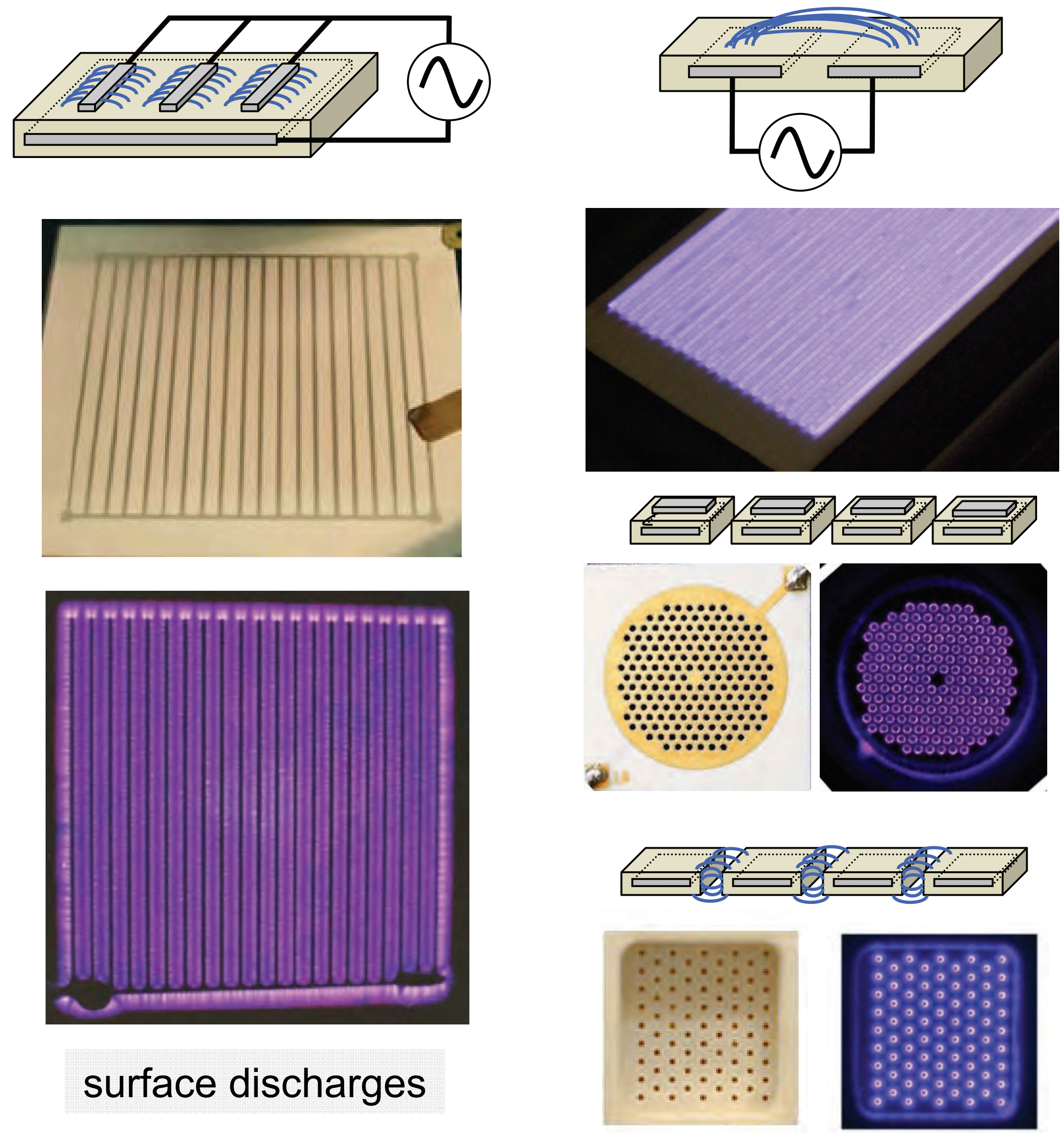


Atmospheric Discharges – Barrier Discharges

- **Dielectric barrier discharge (DBD)** = discharge generated between electrodes separated by dielectric barrier



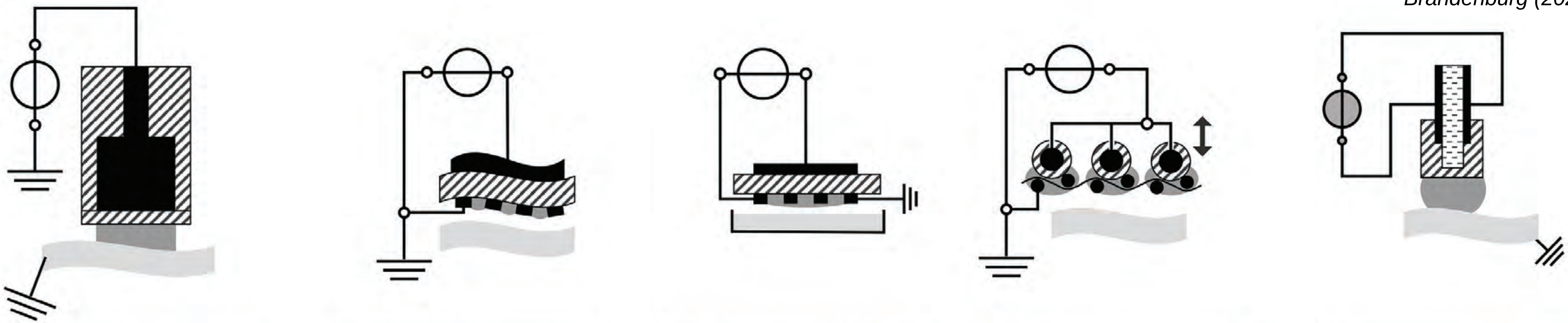
volume discharges

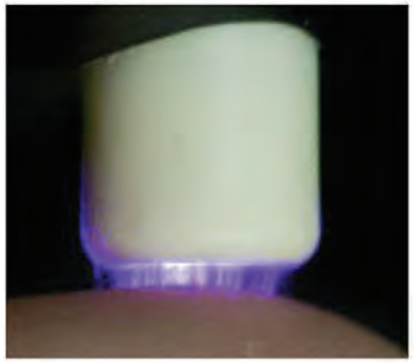


surface discharges

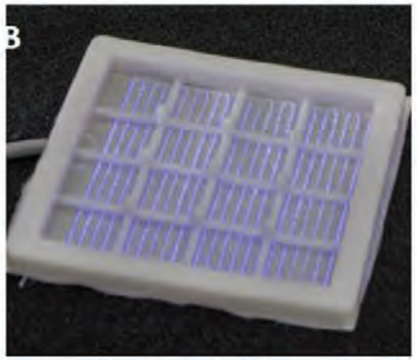
Atmospheric Discharges – Barrier Discharges

Brandenburg (2023)

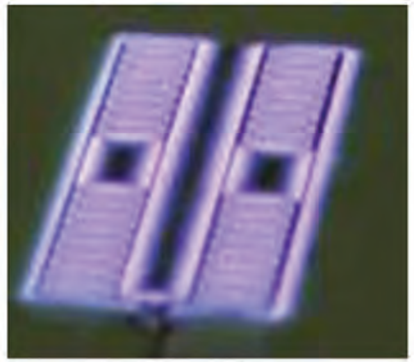




HAWK Göttingen



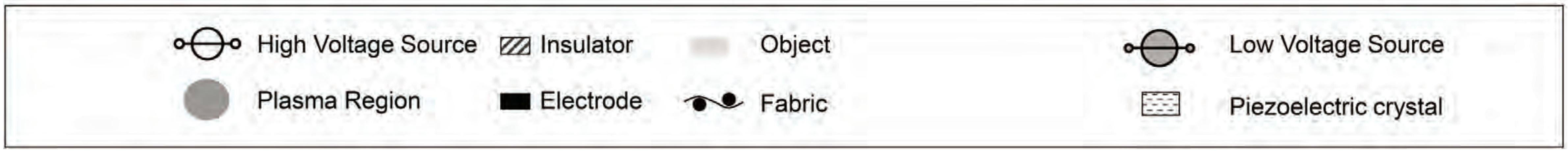
INP Greifswald



INP Greifswald

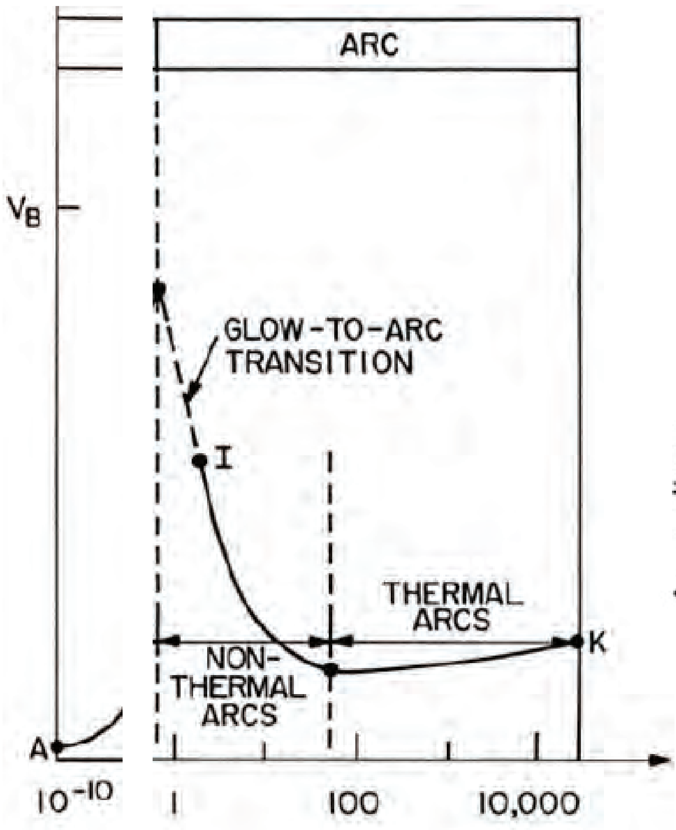
INP Greifswald

relyon plasma Regensburg

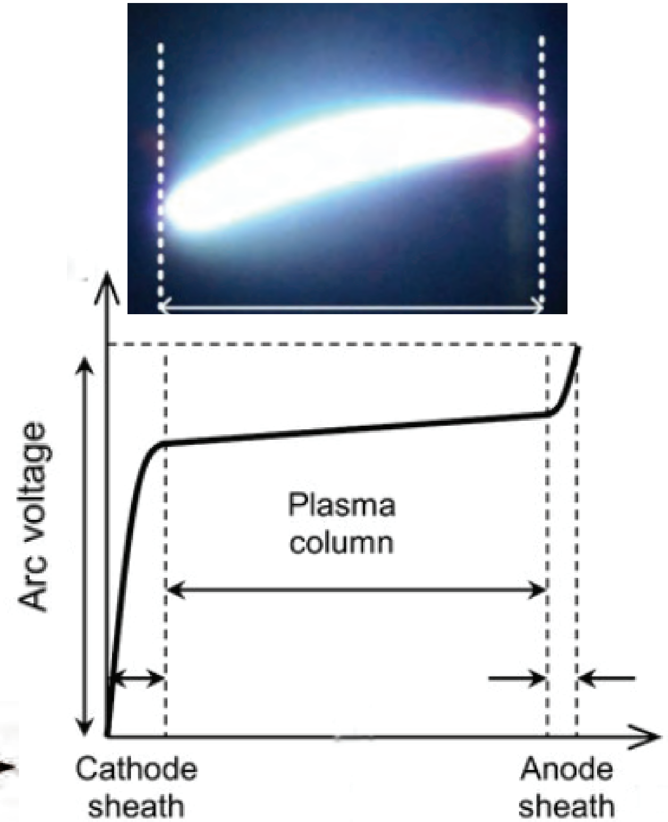


Atmospheric Discharges – Arc Discharges

- **Arc discharge** = discharge characterized by high currents (> 1 A) and a relatively low voltage drop (< 100 V).



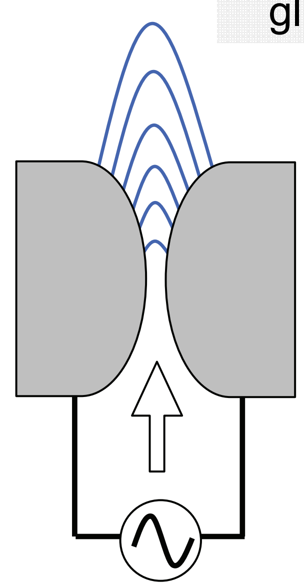
V-I characteristics

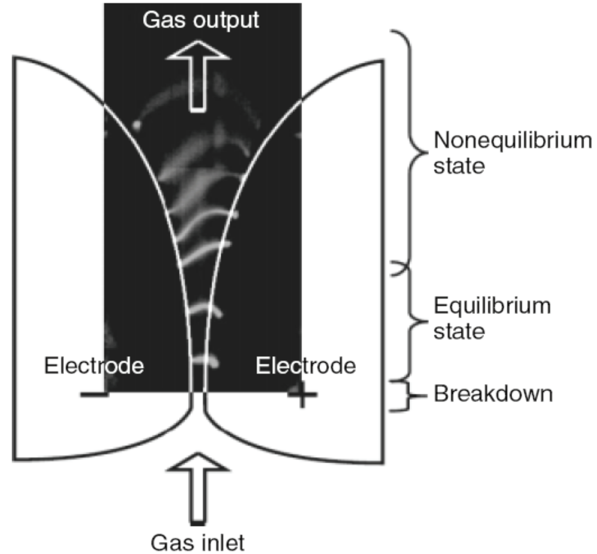


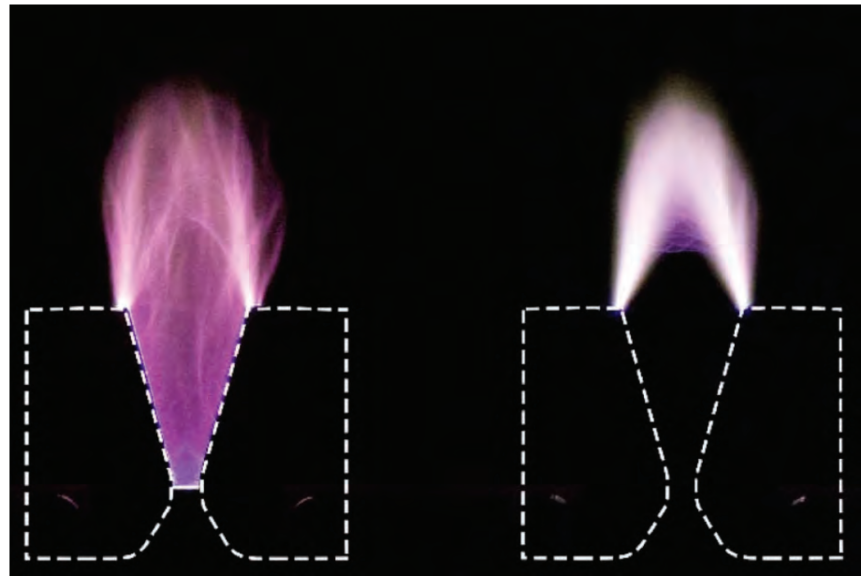
Distribution of potential in arc discharge

Corbella (2019)

gliding arc



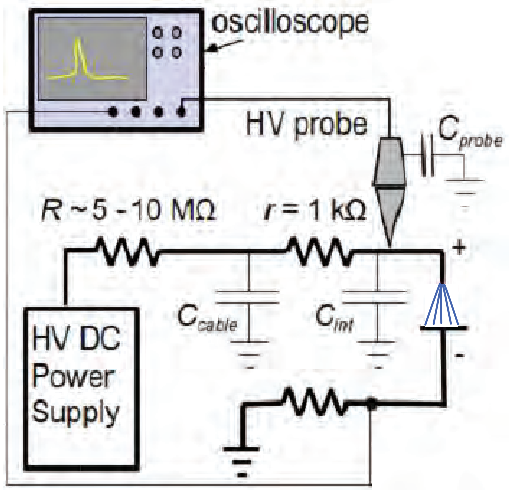




- variation of pressure, high currents
- plasma thermalization, high ionization degree
- intense radiation, electrode melting
- short arc = spark

Atmospheric Discharges – Spark Discharges

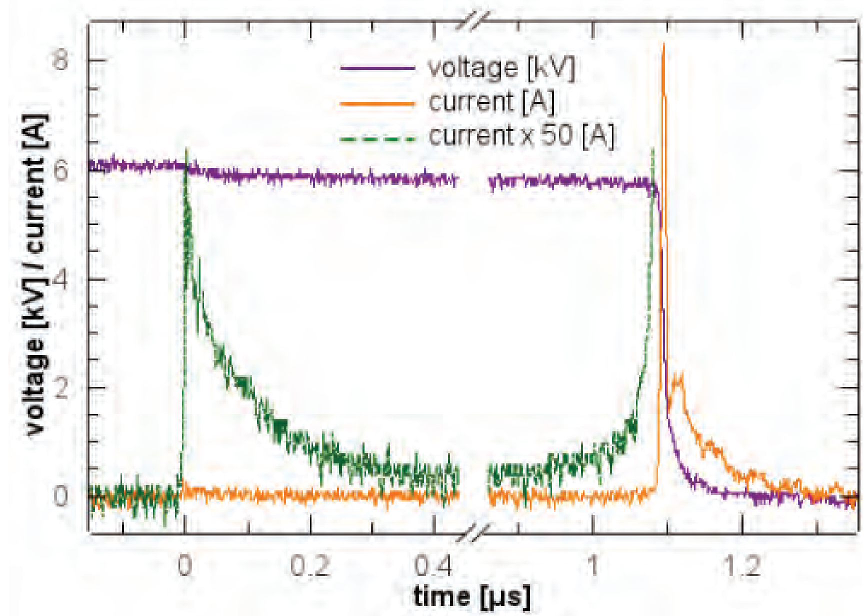
- **Spark discharge** = discharge similar to arc, but momentary not continuous
- **Transient spark (TS) discharge** = DC driven self-pulsating discharge of streamer–to–spark transition



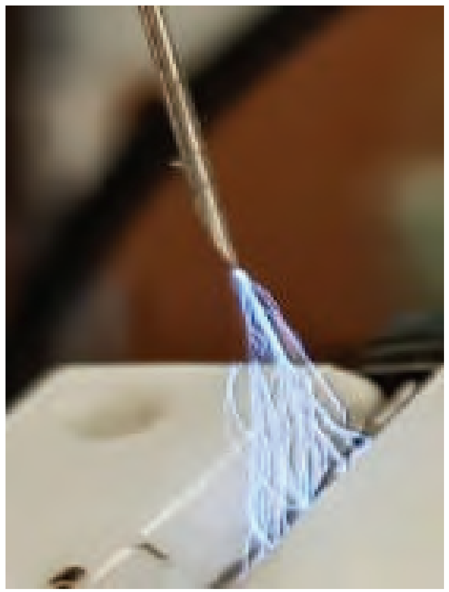
- periodic charging/discharging of internal capacity (C ~ 30 pF)
- frequency (f ~ 1-10 kHz) controllable by applied voltage

Phases of TS:
- corona
- streamer pulse (up to 100 mA)
- streamer–to–spark (< 1 mA)
- strong spark pulse (~ A, 10 ns)
- relaxation (charging) phase

Janda (2010)



V-I wavefoms of streamer-to-spark transition



Atmospheric Discharges – Plasma Jets

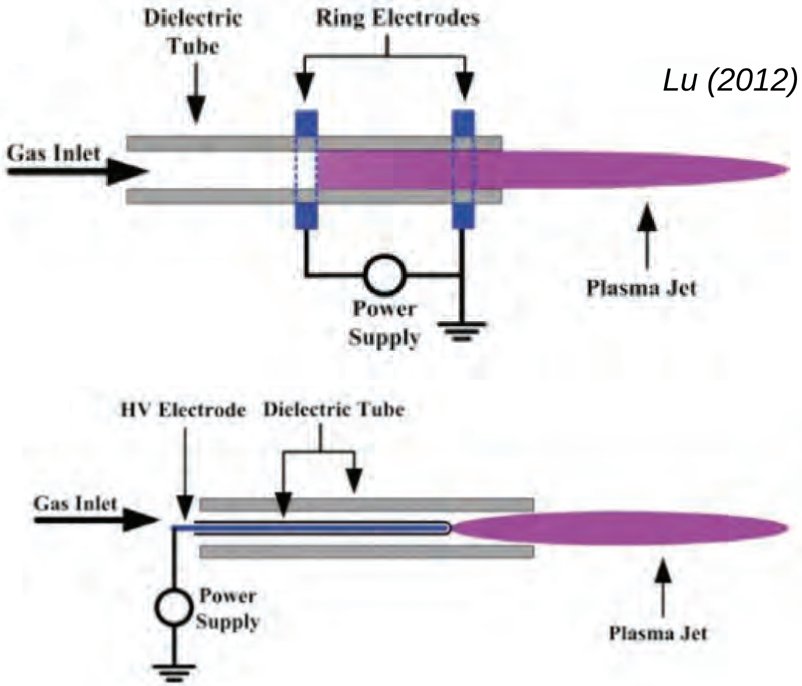
- **Plasma jet** – discharge in a form of jet, utilizing gas blown through the discharge region excited by a plasma

plasma pencil *... Janča (1999), Laroussi (2005)*
plasma needle *... Stoeffels (2002)*

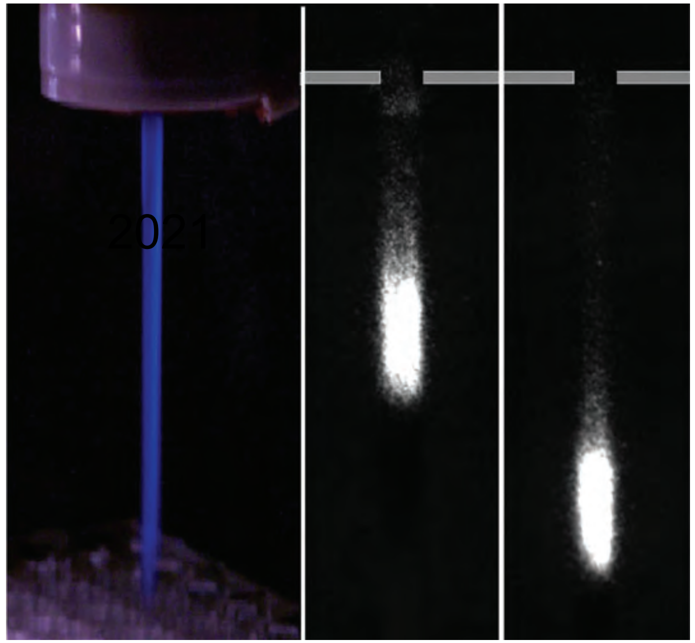
- power supply: DC, AC, RF or MW
- type of discharge: barrier, corona, glow
- feed gas: usually He or Ar

Typical industrial frequencies:
AC: 1-20 kHz
RF (radio-frequency): 13.56 MHz
MW (microwave): 2.45 GHz

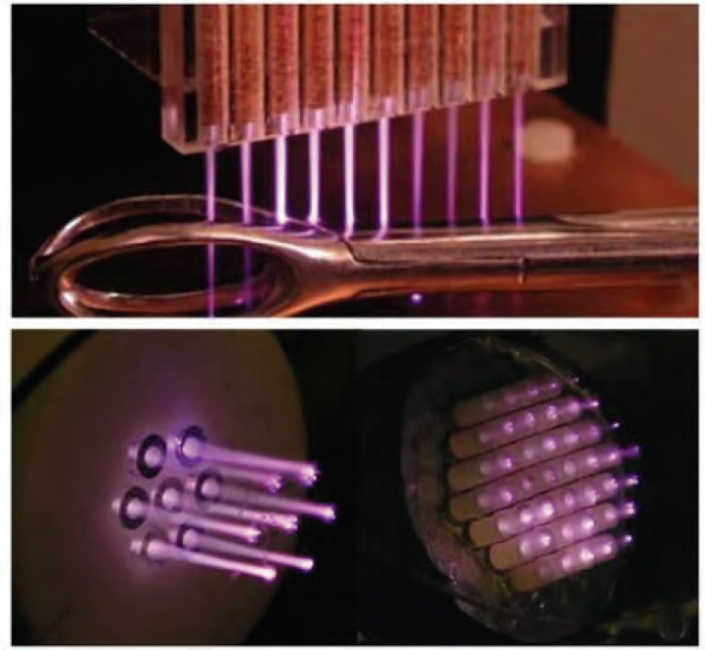
Lu (2012)



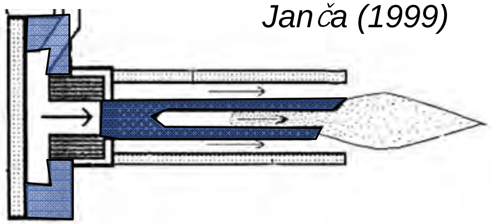
Laroussi (2008)



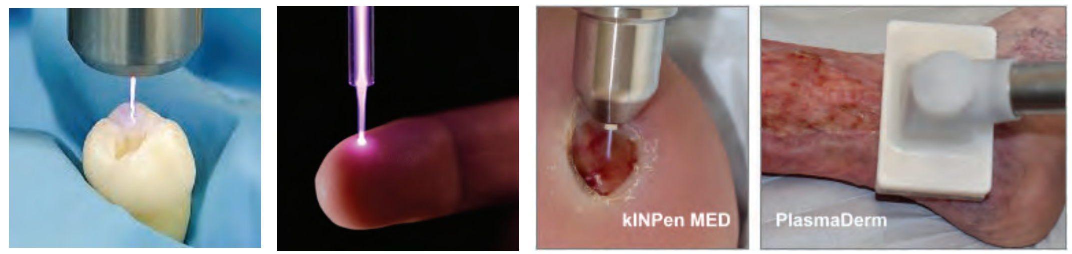
Nie (2014)



Janča (1999)

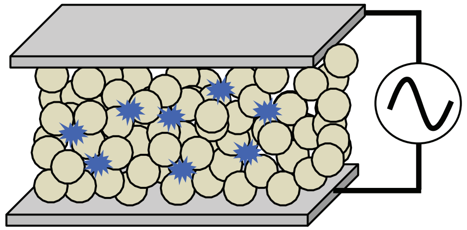


plume/jet turns out to be a series of high-velocity plasma “bullets” travelling at high speeds (~ 10^5 m/s)

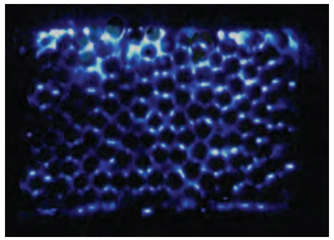


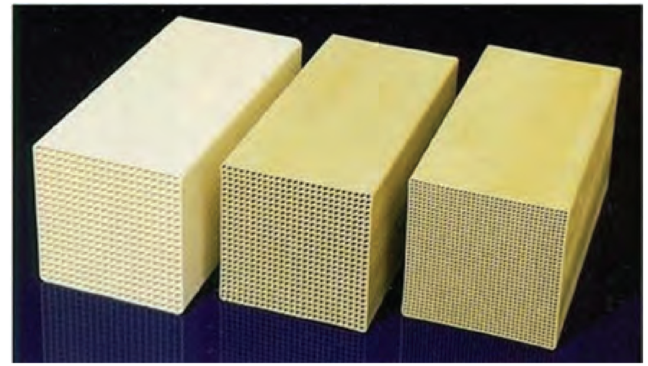
Atmospheric Discharges ... in a Contact with Solids

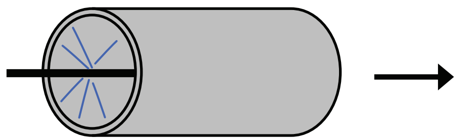
- Discharge in a contact with materials (foams, pellets, honeycombs), coated with catalyst (metals or metal oxides)



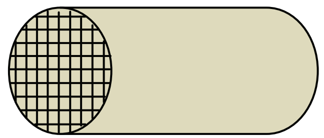
AC,
pulsed



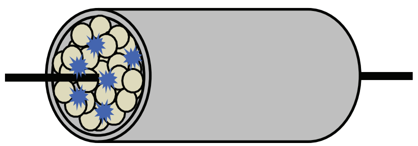




plasma discharge



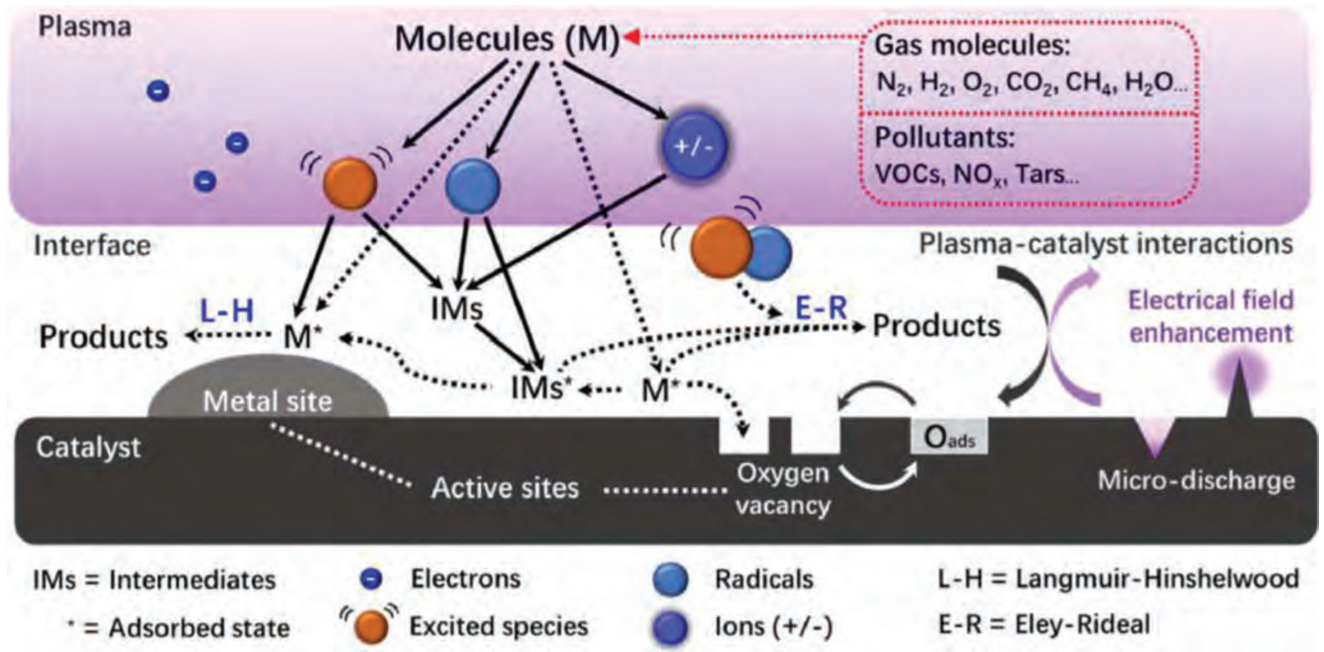
catalyst bed



discharge plasma vs. catalyst

combination of plasma and materials (catalysts) can affect chemical reactions (higher reaction rate, higher selectivity, lower yield of undesired by-products, possible synergy, etc.)

Bogaerts (2020)

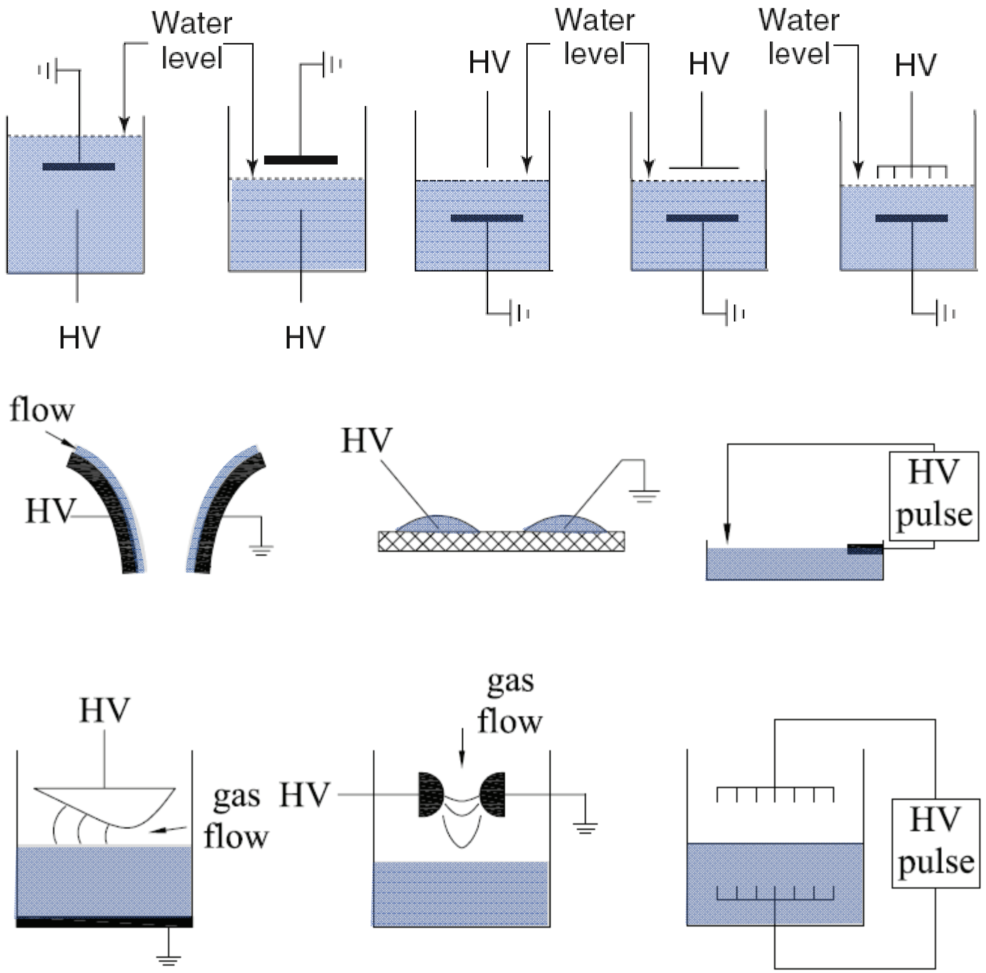


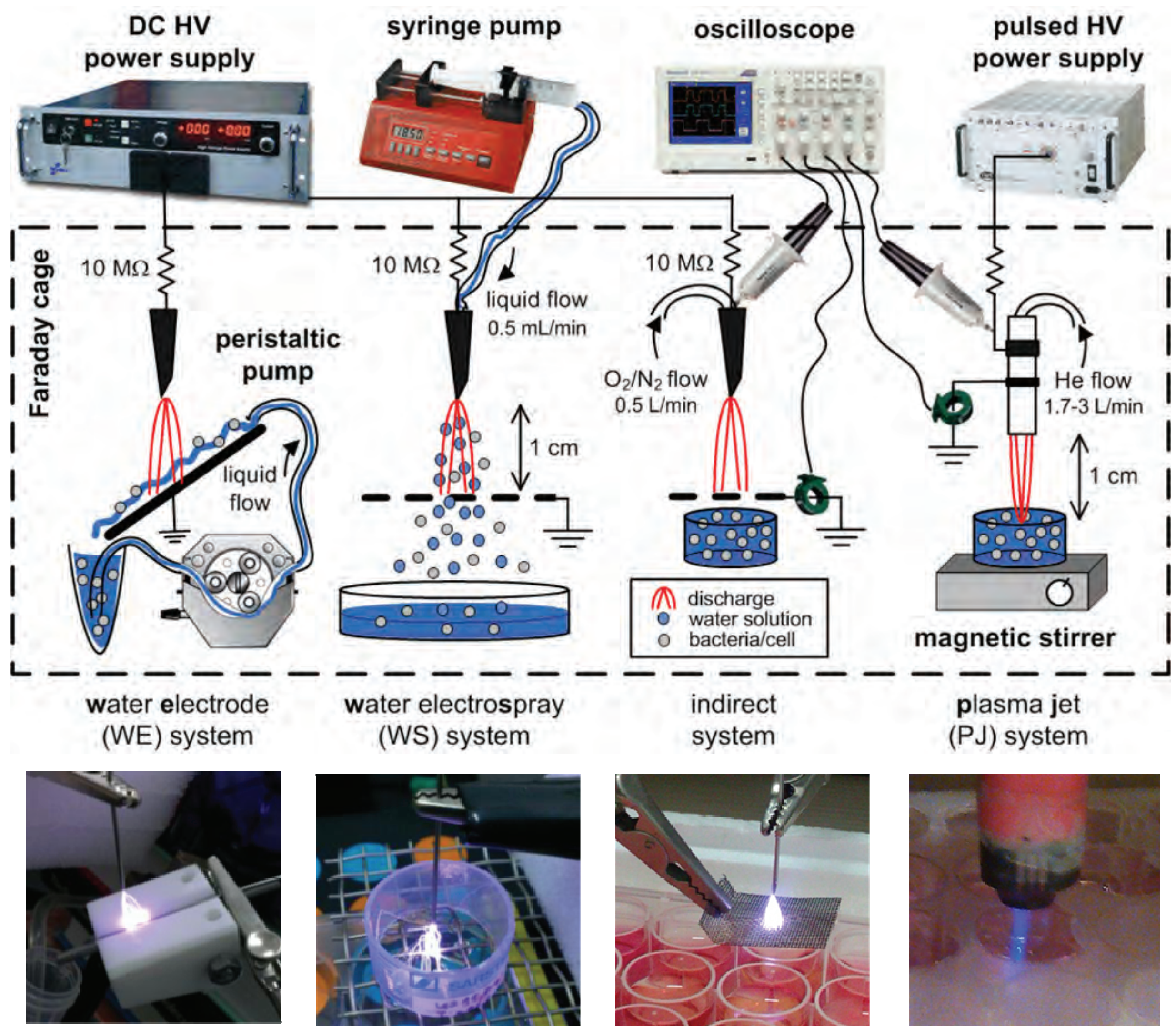
Key mechanisms and species in plasma-catalyst surface

Atmospheric Discharges … in a Contact with Liquids

- Discharges can be generated in gas, in gas in a contact with liquids or directly in liquids

Hensel (2010)

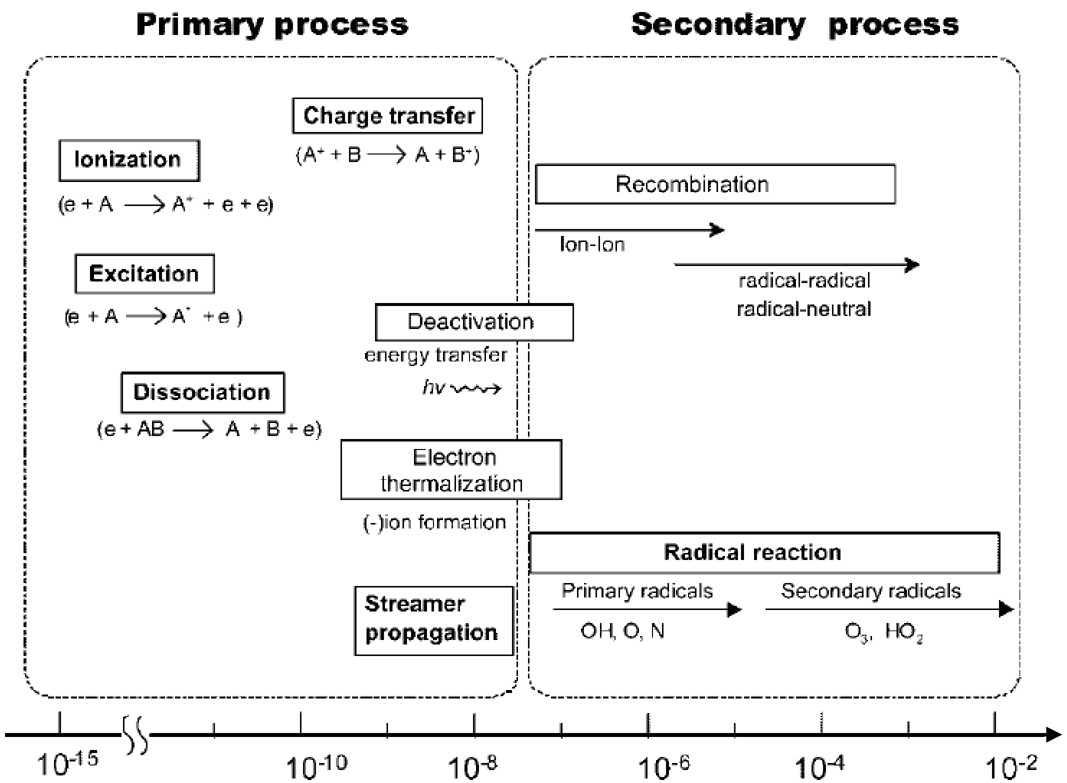




Systems for direct and indirect exposure of liquid to plasma

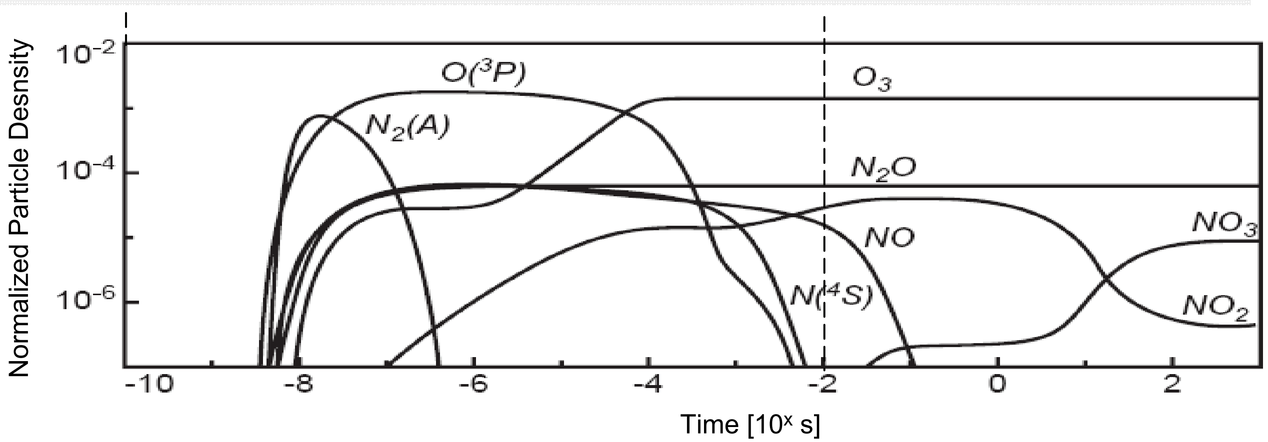
- Interaction of plasma with liquids results in formation of so-called **plasma activated liquids** (PAL)

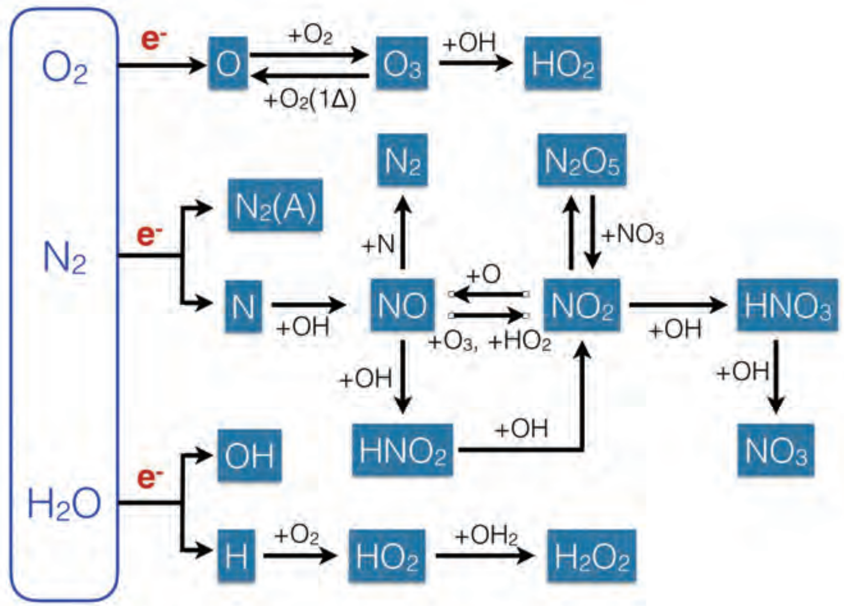
Elementary Processes and Reactions in Atmospheric Plasma



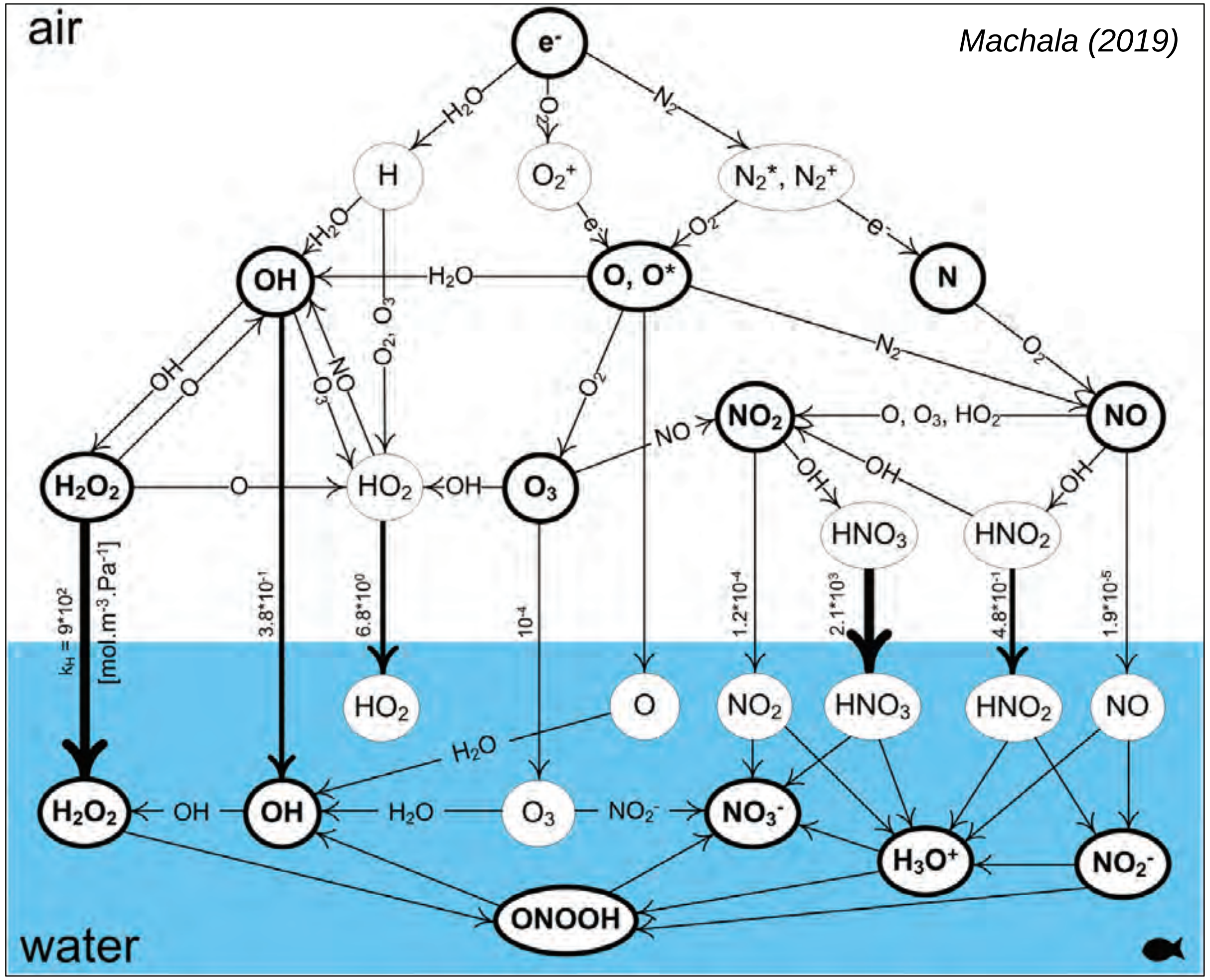
Timescales of collisional and transport processes in atmospheric plasmas

Electron/Molecular Reactions			
Excitation:	$e^- + A_2$	→	$A_2^* + e^-$
Dissociation	$e^- + A_2$	→	$2A + e^-$
Attachment	$e^- + A_2$	→	A_2^-
Dissociative attachment	$e^- + A_2$	→	$A^- + A$
Ionization	$e^- + A_2$	→	$A_2^+ + 2e^-$
Dissociative ionization	$e^- + A_2$	→	$A^+ + A + e^-$
Recombination	$e^- + A_2^+$	→	A_2
Detachment	$e^- + A_2$	→	$A_2 + 2e^-$
Atomic/Molecular Reactions			
Penning Dissociation	$M^* + A_2$	→	$2A + M$
Penning Ionization	$M^* + A_2$	→	$A_2^+ + M + e^-$
Charge Transfer	$A^{\pm} + B$	→	$B^{\pm} + A$
Ion Recombination	$A^- + B^+$	→	AB
Neutral Recombination	$A + B + M$	→	$AB + M$
Decomposition			
Electronic	$e^- + AB$	→	$A + B + e^-$
Atomic	$A^* + B_2$	→	$AB + B$
Synthesis			
Electronic	$e^- + A$	→	$A^* + e^-$
Atomic	$A^* + B$	→	AB
	$A + B$	→	AB





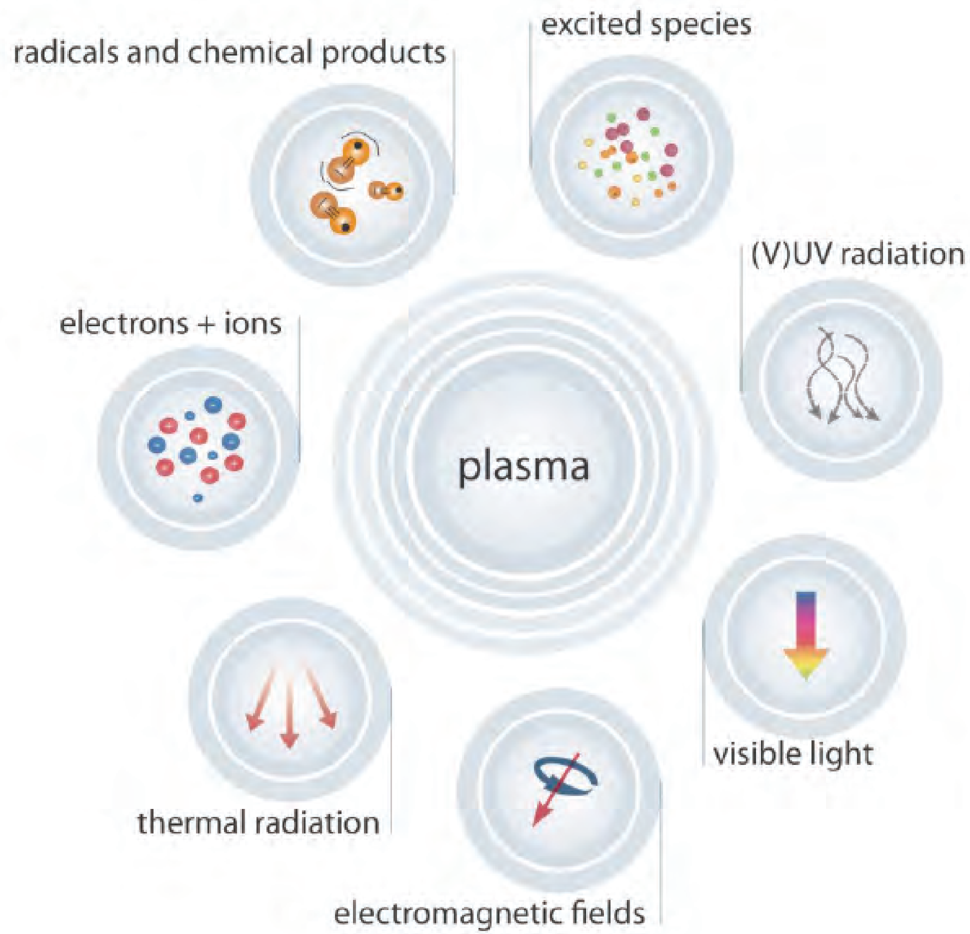
Reactions in Atmospheric Plasma in a Contact with Water



the most important species are in bold,
number are Henry's law solubility coefficients

- Atmospheric plasma
  gaseous and aqueous reactions result in formation of **reactive oxygen and nitrogen species** (RONS)

- Besides the effect of neutral RONS, plasma can also affect target others species, heat, UV radiation and electromagnetic fields.

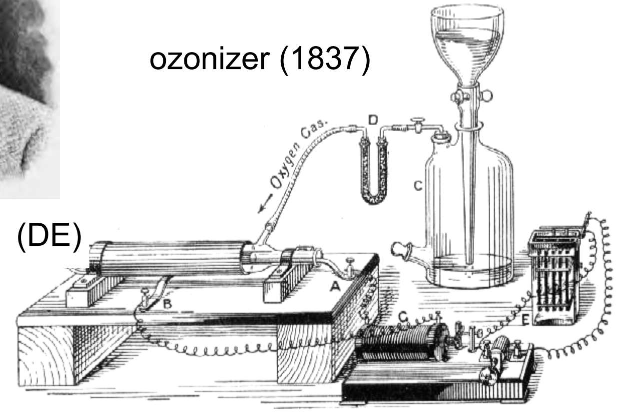


Mechanisms/factors of plasma

History of Atmospheric Plasma Applications

E. W. Siemens (DE)

ozonizer (1837)



Application of electricity to agriculture (1783, Bertholon)

First installation of electrostatic precipitator (1907, Pinole US)

First installation of ozonizer (1903, Nice FR)

Nitrogen fixation by arcs (1903, Birkeland-Eyde)

Violet Ray Machine electrotherapy (1920s)

Sterilization of medical tools (1960s)

First test of NOx/SOx removal (1970s, Masuda JP)

Inactivation of bacteria (1990s)

Manipulations of cells (2000s, Stoeffels NL)

ICPM-1 (2007, Fridman US)

Application of Atmospheric Plasmas

- **Environmental applications**
  - ✓ air pollution control (exhaust gas treatment – VOC, NOx, SO_2, CO_2, particulate matter)
  - ✓ water cleaning (ozone generation)
  - ✓ municipal solid waste (plasma torches)
- **Biomedical and agricultural applications**
  - ✓ volume/surface decontamination and sterilization (instruments/tissues/wounds) … therapy (cancer, ulcers)
  - ✓ seed germination, plants growth
  - ✓ food and package processing
- **Energy applications**
  - ✓ fuel (CH_4) reforming and H_2 generation (power-to-X)
  - ✓ plasma assisted combustion and ignition
- **Material applications**
  - ✓ welding and cutting
  - ✓ surface modification and activation (cleaning, etching, deposition, implantation)
- **Optical applications**
  - ✓ light sources, plasma display panels
  - ✓ smoke detectors

14th International Symposium on Non-thermal/Thermal Plasma for Pollution Control and Sustainable Energy (ISNTP)

Bratislava, Slovakia, Sept 27 – Oct 1, 2026

History: 1992 Cambridge … 2018 Montegrotto, 2022 Sapporo, 2024 Gangneung

Topics: Plasma fundamentals, diagnostics, modeling and simulations, Air pollution control, Water and wastewater treatment, Remediation of hazardous compounds (PFOS, PFOA, Dioxin, PCBs), Plasma catalysis, Plasma assisted combustion, Fuel reforming, Power-to-X (X = H2, CH4, NH3, MeOH, NOx), Biomedical applications, Agriculture and food processing

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