Plasma physics

2023 winter s. 2/1 , C+Ex
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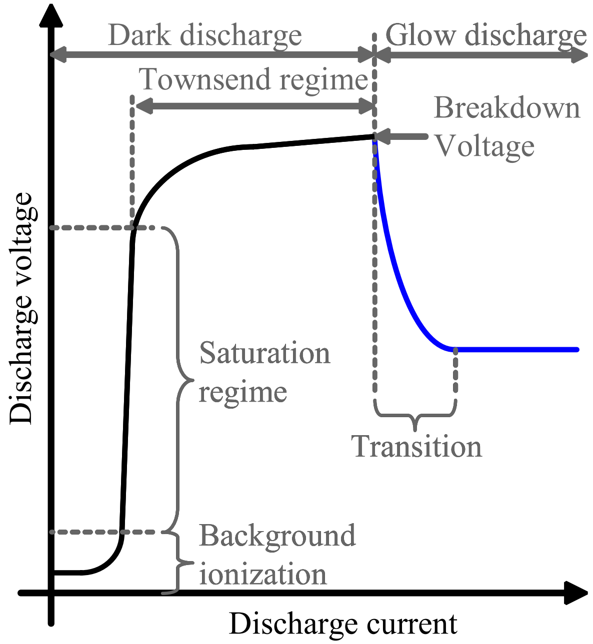
- Glow discharge
- Arc discharge
- RF, μW discharge

Townsend avalanche, Townsend breakdown

from previous class

$$n_e(x) = n_e(0)\exp(\bar{\alpha}x)$$



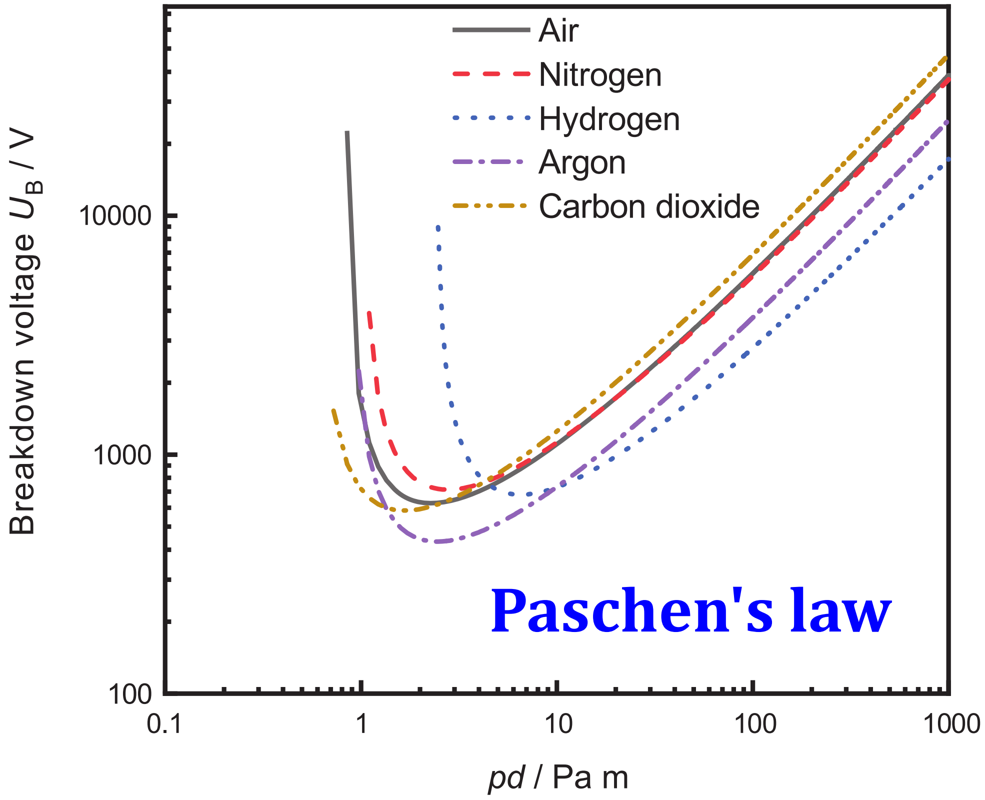
Townsend breakdown $\bar{\alpha}d \geq \ln(1+{\epsilon_i}^{-1})$

$$U_\mathrm{B}(pd) = \frac{Bpd}{\ln\left[{}^{Apd}\!/\!{}_{\ln(1+{\epsilon_i}^{-1})}\right]}$$

e ... Euler number

$$U_\mathrm{B,\,min} = \frac{\mathrm{e}B}{A}\ln(1+{\epsilon_i}^{-1})$$

$$(pd)_\mathrm{min} = \frac{\mathrm{e}}{A}\ln(1+{\epsilon_i}^{-1})$$



Paschen's law

Ollegott K. et al. *Chem. Ing. Tech.* 92 2020 1.
doi: 10.1002/cite.202000075

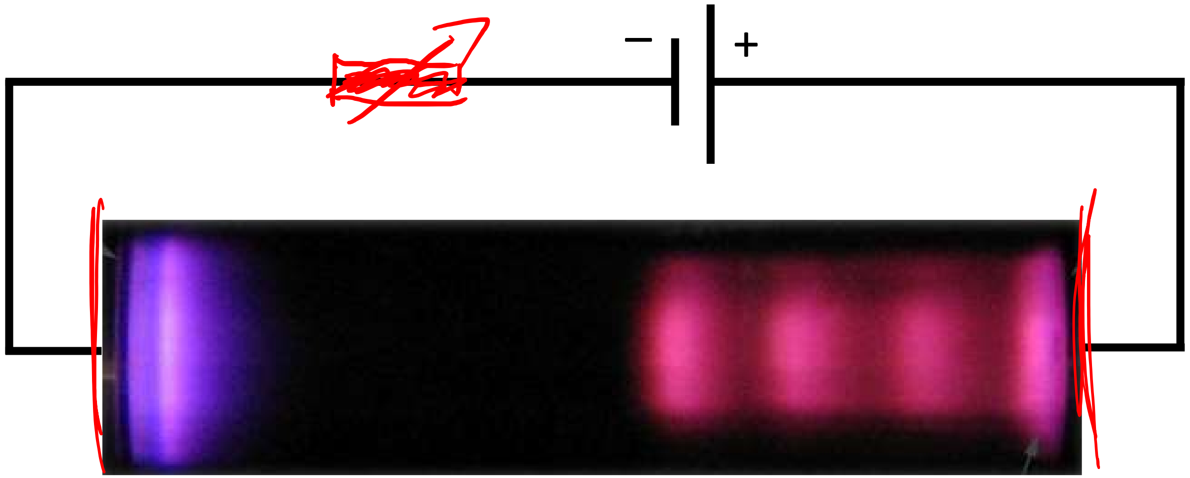
Glow discharge

{Czech: Doutnavý výboj}
{Slovak: Tlejúci výboj}

Townsend breakdown leads to glow discharge.

Typical glow discharge DC, 10 – 1000 Pa, 300 – 500 V, 0.1 – 100 mA

The reduced pressure increases the mean free path
so that electrons can be accelerated at a given length by a lower voltage. $U_\mathrm{B}(pd)$



Glow discharge — Cathode layer

Aston dark space

secondary electrons with low energy ≈ 1 eV
no excitation or ionization, ≈ one mean free path

Cathode glow

excitation by accelerated electrons and deexcitation
length depends on the gas and pressure

Cathode dark space / Crookes dark space

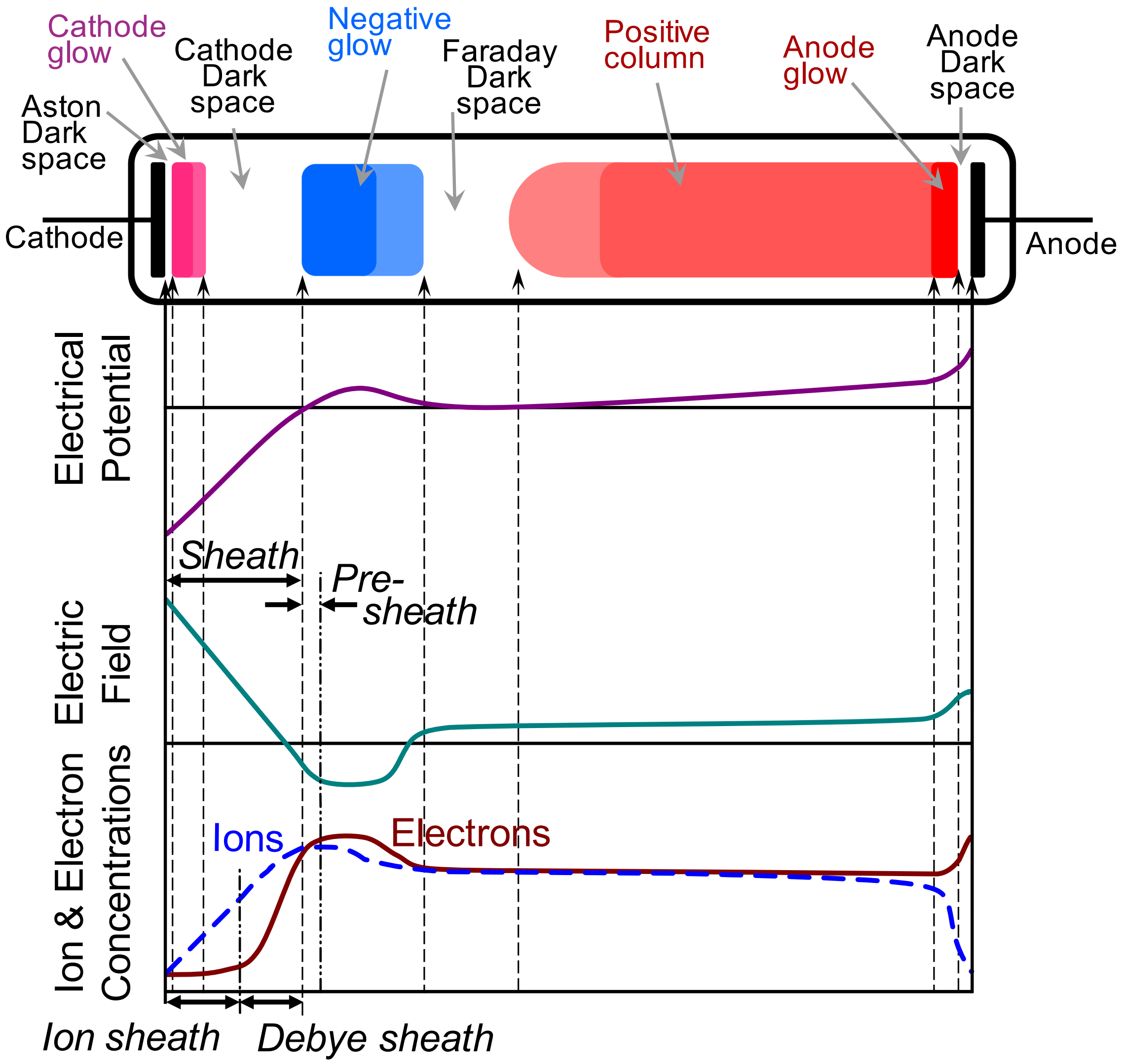
ionization by accelerated electrons
strong el. field separates charges ⇒ no recombination

Negative glow

accumulated slower electrons and ions
bremsstrahlung radiation (bluish)
typically brightest part of discharge

Faraday dark space

low electric field, low energy of electrons
slower electrons and ions ⇒ recombination



Glow discharge — Anode layer

Positive Column

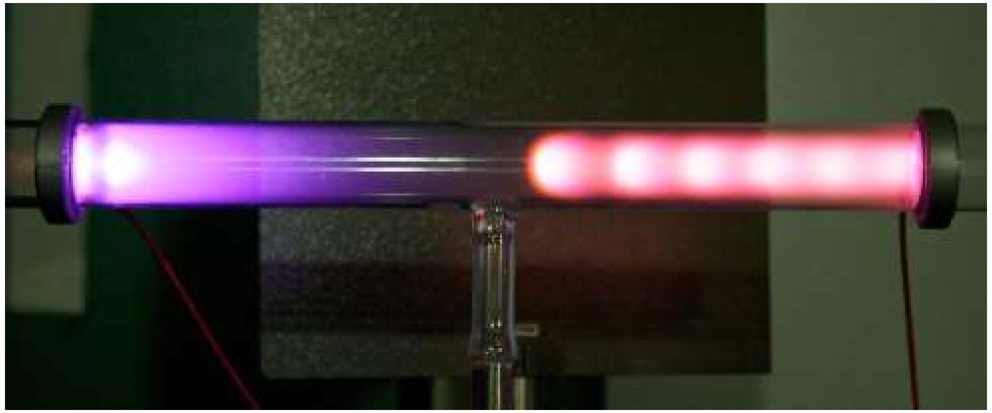
low electric field ≈ 1 V cm^{-1}
quasi-neutral plasma
electron drift velocity < thermal velocity
striations (standing waves) v_e modulation

Anode glow

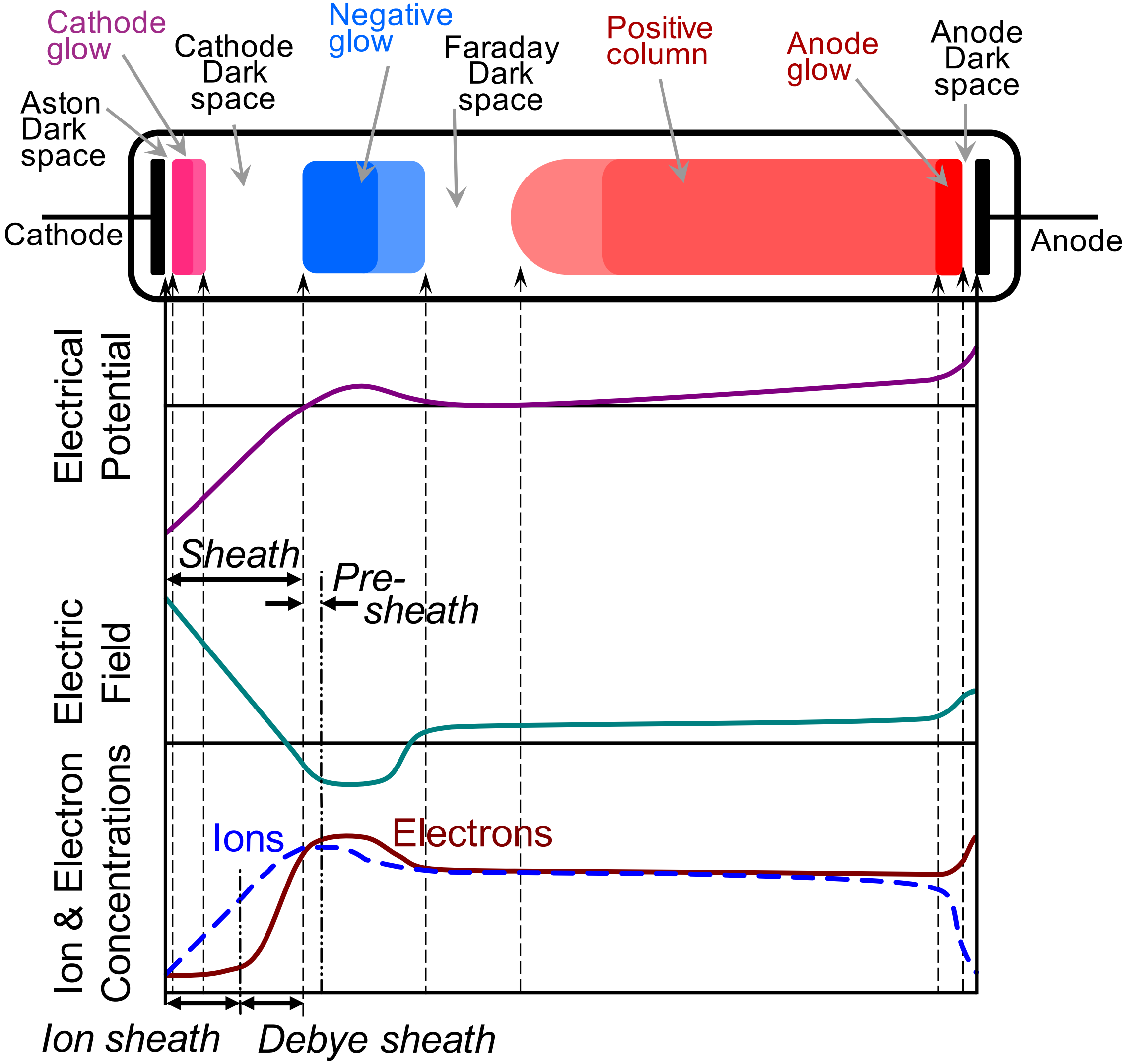
ions are repelled from anode ⇒ electric field
accelerated electrons excites neutrals

Anode dark space

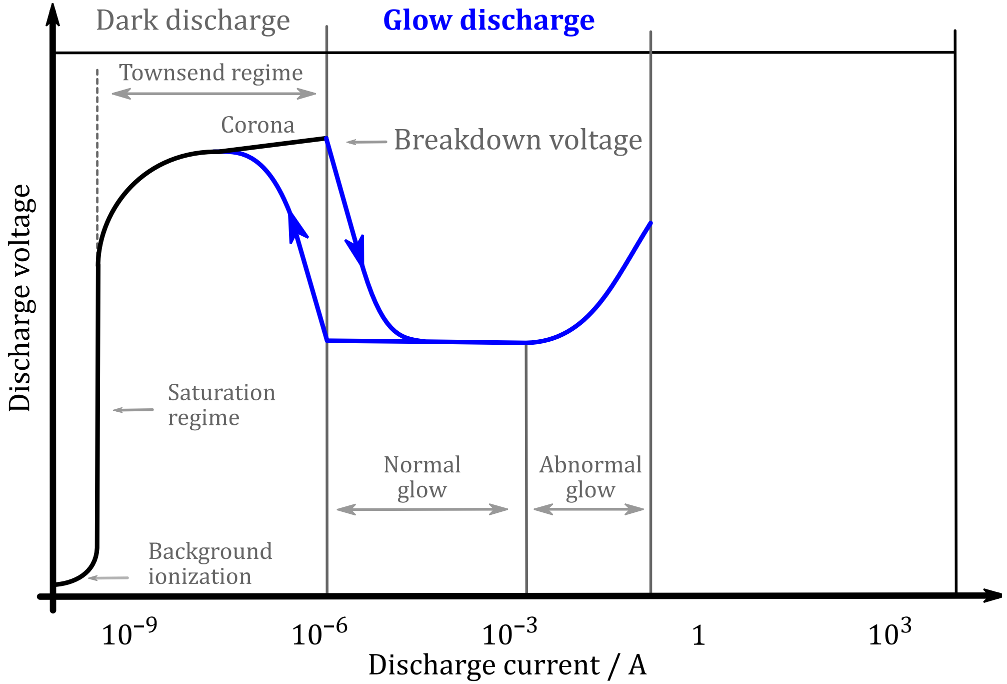
ionization by accelerated electrons, no recombination

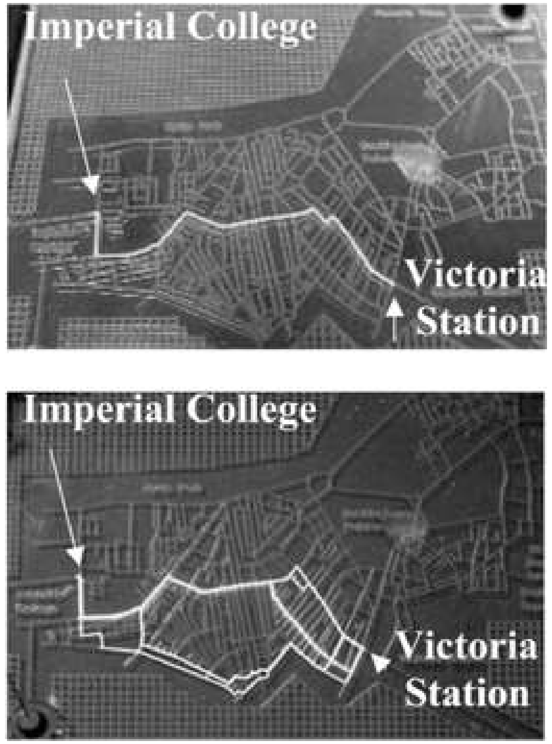


Wikimedia Commons



Glow discharge applications





Dittrich P. S. *Lab on a Chip* 8 (2008) 1769.
doi: 10.1039/b816252m

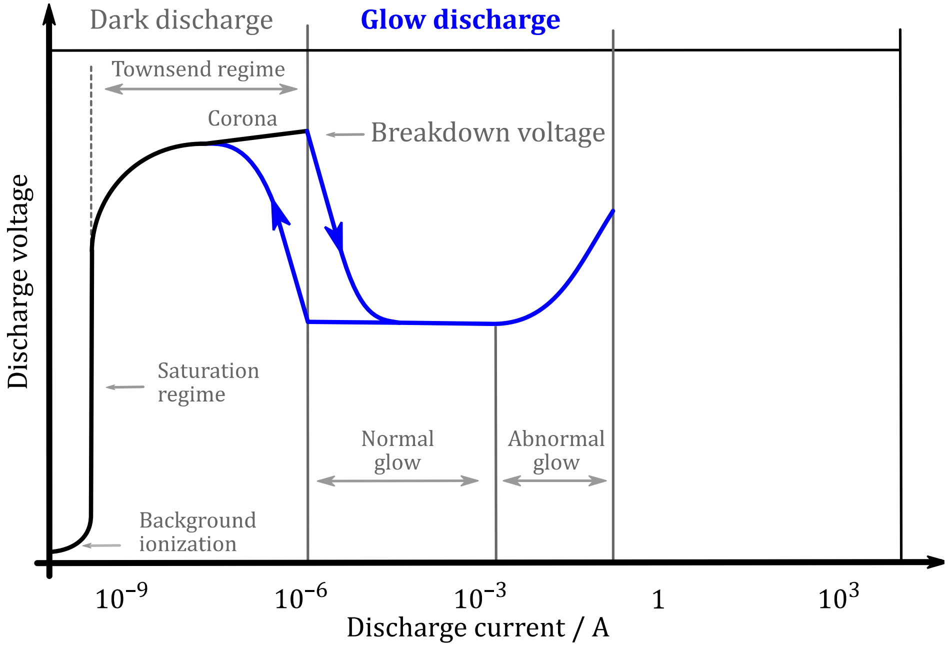
Applications:

- Lightning
- Voltage-regulator tube
- Glow Discharge Mass Spectrometry (atomization)
- Surface modification (implanting ions, etching, cleaning)
- and many others

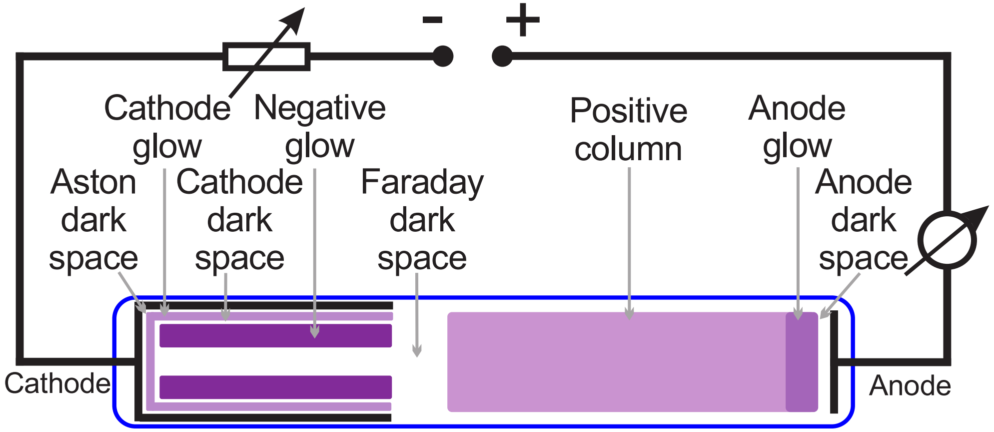
Abnormal glow discharge

is used in most industrial applications due to

its higher current density (10 – 100 mA)
higher ion energy
and stability.



hollow cathode



Karatodorov S. I. *Dissertation thesis* (2017)
Bulgarian Academy of Sciences.

- longer path of electrons “pendulum effect”
- photoionization
- larger surface area ⇒ higher currents
- limited sputtering into the discharge tube

Arc discharge

Enhanced electron emission from metals

ϕ … work function

Richardson–Dushman equation

Thermionic emission

$$j_{\text{therm}} = \lambda_{\text{R}}\, A_0\, T^2 \exp\left(-\frac{\phi}{k_{\text{B}} T}\right) \qquad A_0 = \frac{4\pi m_e k_{\text{B}}^2 q_e}{h^3}$$

(A m^{-2})

Schottky emission

$$j_{\text{Schottky}} = \lambda_{\text{R}}\, A_0\, T^2 \exp\left(-\frac{(\phi - \Delta W)}{k_{\text{B}} T}\right)$$

(Field enhanced emission – tunneling)

barrier lowering $\Delta W = \sqrt{\dfrac{q_e^3 E}{4\pi\varepsilon_0}}$

Cathodic arc spots, sputtering
(explosive emission)

Child-Langmuir law (three-halves-power law)

$$\nabla^2\varphi = -\frac{\rho}{\varepsilon_0} \qquad \text{1D}$$

$$\varphi(x=0)=0$$

$$\varphi(x=L_\mathrm{D})=U_\mathrm{D}$$

$$\left.\frac{\mathrm{d}\varphi}{\mathrm{d}x}\right|_{x=0}=\underline{0}$$

$$v(x=0)=\underline{0}$$

$$\rho=\frac{j}{v}$$

$$\tfrac{1}{2}mv^2=q_e\varphi \quad \Longrightarrow v=\sqrt{\frac{2q_e\varphi}{m}}$$

$$\nabla^2\varphi=\frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}\varphi}{\mathrm{d}x}=\frac{j}{\varepsilon_0}\sqrt{\frac{m}{2q_e}}\,\varphi^{-\frac{1}{2}}=\Lambda\,\varphi^{-\frac{1}{2}}$$

$$\Lambda=\frac{j}{\varepsilon_0}\sqrt{\frac{m}{2q_e}}$$

$$\frac{\mathrm{d}\varphi'}{\mathrm{d}x}=\Lambda\,\varphi^{-\frac{1}{2}} \qquad \varphi'=\frac{\mathrm{d}\varphi}{\mathrm{d}x} \qquad \mathrm{d}x=\frac{\mathrm{d}\varphi}{\varphi'}$$

$$\varphi'\mathrm{d}\varphi'=\Lambda\,\varphi^{-\frac{1}{2}}\,\mathrm{d}\varphi$$

$$\tfrac{1}{2}\varphi'^2=\Lambda\,\varphi^{\frac{1}{2}}+\cancel{K_1} \qquad K_1=0$$

$$\varphi'=2\,\Lambda^{\frac{1}{2}}\,\varphi^{\frac{1}{4}}$$

$$\varphi^{-\frac{1}{4}}\,\mathrm{d}\varphi=2\,\Lambda^{\frac{1}{2}}\,\mathrm{d}x$$

$$\tfrac{2}{3}\varphi^{\frac{3}{4}}=\Lambda^{\frac{1}{2}}\,x+\cancel{K_2} \qquad K_2=0$$

$$\Lambda=\tfrac{4}{9}U_d^{\frac{3}{2}}L_\mathrm{D}^{-2}$$

only electrons without collisions

$L_\mathrm{D}=1\ \mathrm{cm}$, $U_\mathrm{D}=300\ \mathrm{V}$

$j_\mathrm{C-L}\approx 10\ \mathrm{mA\,cm^{-2}}$

$$j_\mathrm{C-L}=\frac{4}{9}\varepsilon_0\sqrt{\frac{2q_e}{\underline{m_e}}}\,\frac{U_\mathrm{D}^{3/2}}{\underline{L_\mathrm{D}^2}}$$

⇒ ions play a key role

https://simion.com/definition/childs_law.html

Arc discharge

The arc is established either by the transition from the glow discharge or by the momentary contact of the electrodes and their subsequent separation.

Processes of ionization:

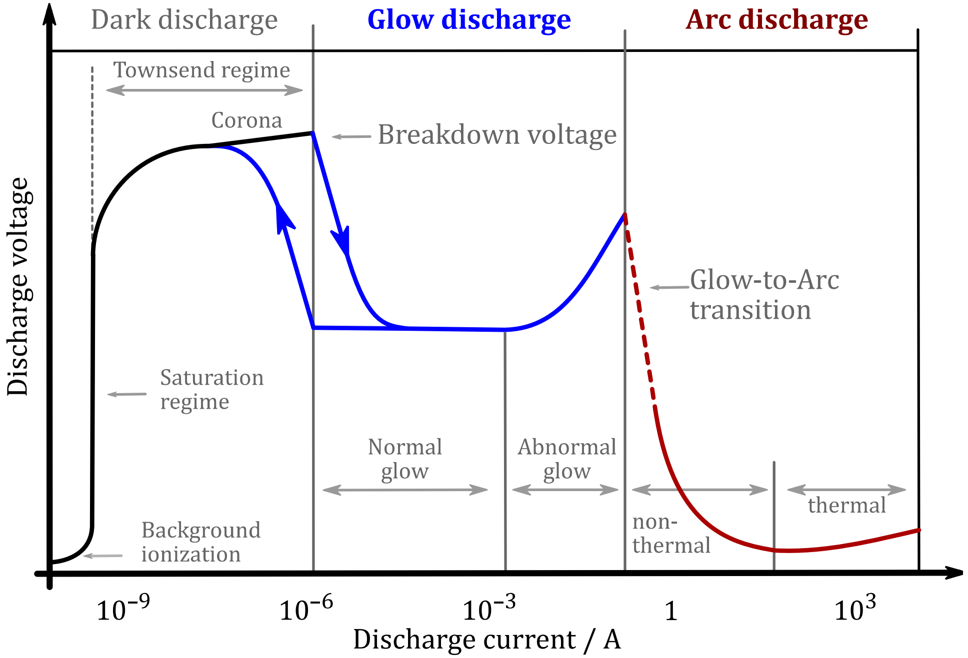
- electron impact, stepwise ionization
- thermal equilibrium (Saha eq.)
- photoionization

The cathode fall is in general on the order of the ionization potential for the working gas, or even lower (1–10 V).

The current density at the cathode can range from 100 to 10^7 A cm^{-2}.

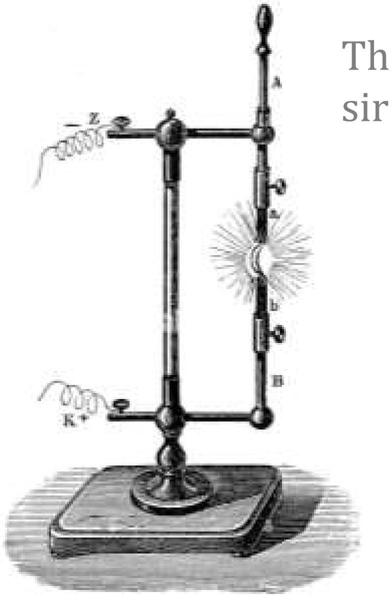
Typical temperature in arcs 1 000 K - 10 000 K up to 20 000 K in arc flash.

AC arc Credit: CC Achgro



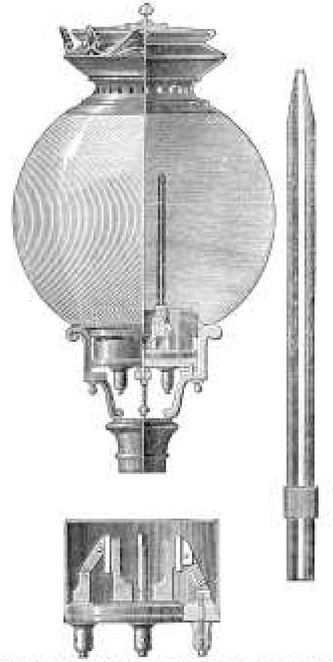
Arc lamps

carbon, tungsten electrodes



ELECTRIC ARC

The first arc lamp 1807 arc
sir Humphry Davy



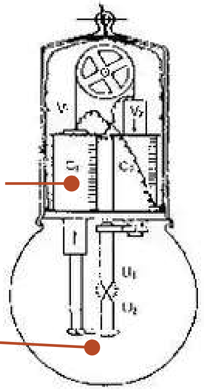
Lampe Jablochkoff munie de son globe. — Armature avec ses porte-charbons. — Bougie électrique.

oldbookillustrations.com

Yablochkov candle 1878
≈ 1 hour

Moonlight tower in New Orleans about 1900

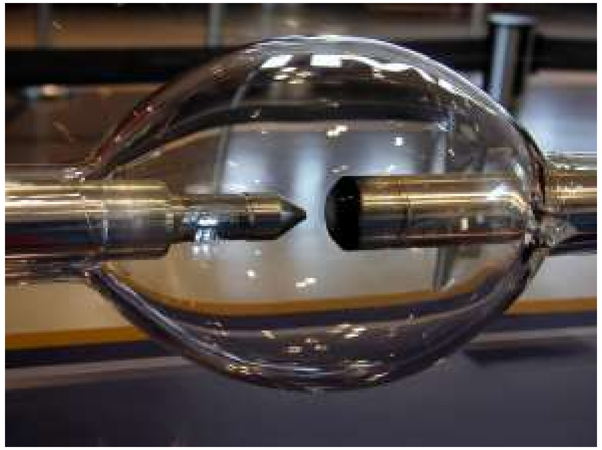
solar.lowtechmagazine.com/2009/01/moonlight-towers-light-pollution-in-the-1800s



coils

electrodes

Arc lamp with electromagnetic self-adjustment 1881
lasting longer, lower flickering
František Křižík (1847-1941)

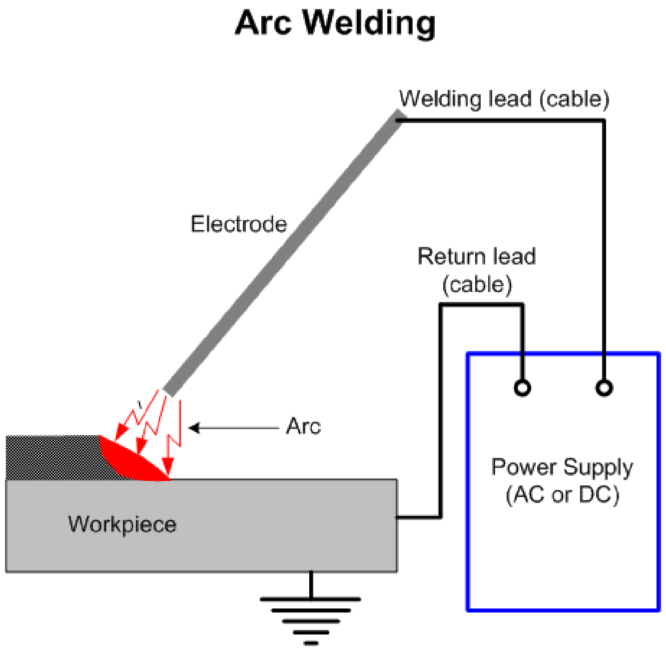


IMAX 15 kW Xe lamp, 25 bar

30 – 60 lm/W

(Incandescent light bulb 16 lm/W)

Arc welding



Credit: CC Substech

The arc parameters strongly depend on the nature and dimensions of the materials.
(Typical MMA “Manual Metal Arc” DC 10 – 50 V, 30 – 200 A)

Arc temperature from 5 000 K – 10 000 K. Iron melts at ≈ 1 800 K.

Example of MMA welder
with invertor
9 kW, 200 A, 6 kg, 170 EUR

Alternating current discharge

At low frequencies (50 or 60 Hz)
characteristics is similar to a DC discharge

Uniform loading of electrodes

Between cycles, some of the ionized particles remain in the area, making it easier and more regular to ignite the discharge.

Radio Frequency discharge

low pressure plasma
(no influence of collisions)

$$m_e \frac{\mathrm{d}^2 x}{\mathrm{d}t^2} = q_e E_0 \cos(2\pi f t)$$

$$v_e = \frac{\mathrm{d}x}{\mathrm{d}t} = \frac{q_e E_0}{m_e} \frac{\overset{1}{\cancel{\sin(2\pi f t)}}}{2\pi f} + C$$

$v_{e\,max}$ $v_{e-\mathrm{max}}$

$$x = -\frac{q_e E_0}{m_e} \frac{\overset{1}{\cancel{\cos(2\pi f t)}}}{(2\pi f)^2} + C_2$$

x_{ampl}

$$\mathcal{E}_{\mathrm{kin}} = \frac{m_e}{2} v_{e\,\mathrm{max}}^2$$

Acceleration and ionization in collisions

Electron losses:

recombination,
attachment,
diffusion.

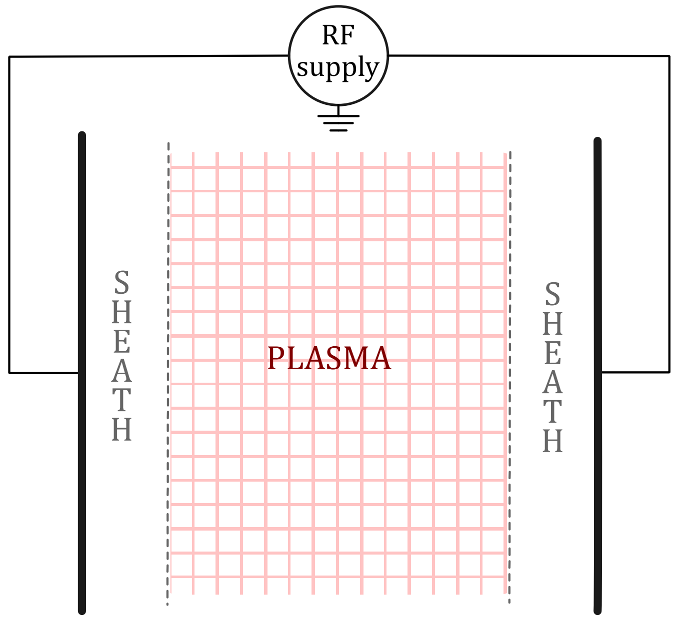
Conditions for breakdown

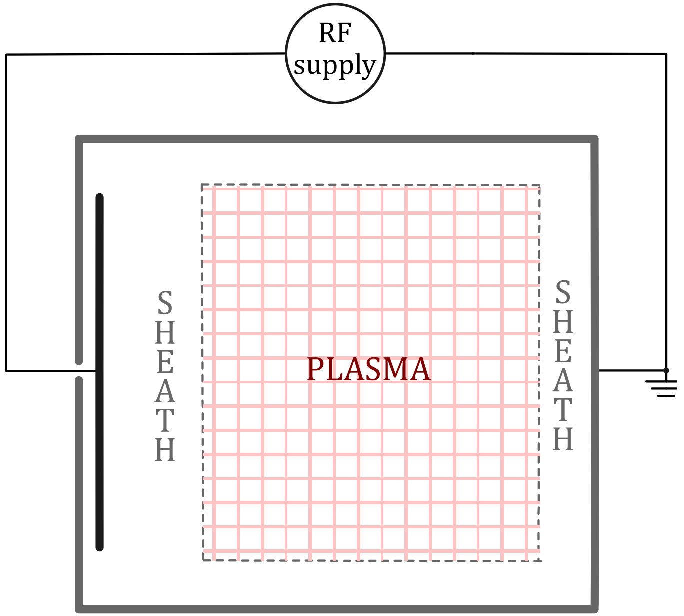
$f_{\mathrm{RF}} = 13.56\ \mathrm{MHz}$
$E_0 = 10\ \mathrm{V\,cm^{-1}}$ $\Longrightarrow$ $\mathcal{E}_{\mathrm{kin}} \approx 11\ \mathrm{eV}$
$x_{\mathrm{ampl}} \approx 2.5\ \mathrm{cm}$

Radio Frequency discharge

Frequency bands designated by the ITU for industrial, scientific and medical (ISM) applications

	Center frequency	Bandwidth
	13.56 MHz	14 kHz
RF	27.12 MHz	326 kHz
300 MHz	40.68 MHz	40 kHz
	2.45 GHz	100 MHz
μW	5.80 GHz	150 MHz
	24.125 GHz	250 MHz





Microwave (μW) discharge

$$v_{e\,max} = \frac{q_e E_0}{m_e}\frac{1}{2\pi f}$$

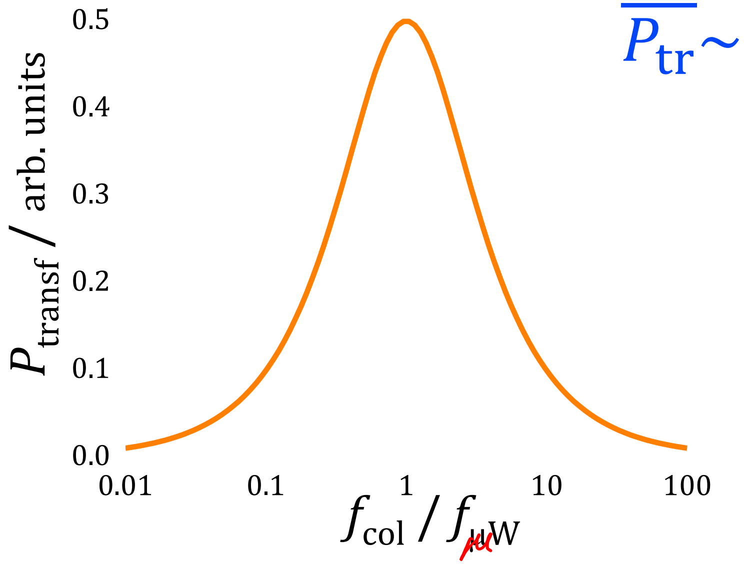
$$\mathcal{E}_{\mathrm{kin}} = \frac{m_e}{2}\left(\frac{q_e E}{m_e}\frac{1}{2\pi f}\right)^2 = \frac{q_e^2 E^2}{8\pi^2 m_e}\frac{1}{f^2}$$

$$\frac{\mathcal{E}_{\mathrm{kin}}}{t} \sim \frac{q_e^2 E_0^2}{m_e}\frac{1}{f_{\mu\mathrm{W}}}$$

$$\overline{P_{\mathrm{tr}}} \sim \frac{q_e^2 E_0^2}{m_e}\left(\frac{f_{\mathrm{col}}}{f_{\mathrm{col}}^2 + f_{\mu\mathrm{W}}^2}\right)$$

collision plasma

$$f_{\mu\mathrm{W}} = 2.45\ \mathrm{GHz}$$
$$E_0 = 30\ \mathrm{V\ cm^{-1}}$$
$$\Longrightarrow$$
$$\mathcal{E}_{\mathrm{kin}} \approx 30\ \mathrm{meV}$$
$$x_{\mathrm{ampl}} \lesssim 3\ \mu\mathrm{m}$$



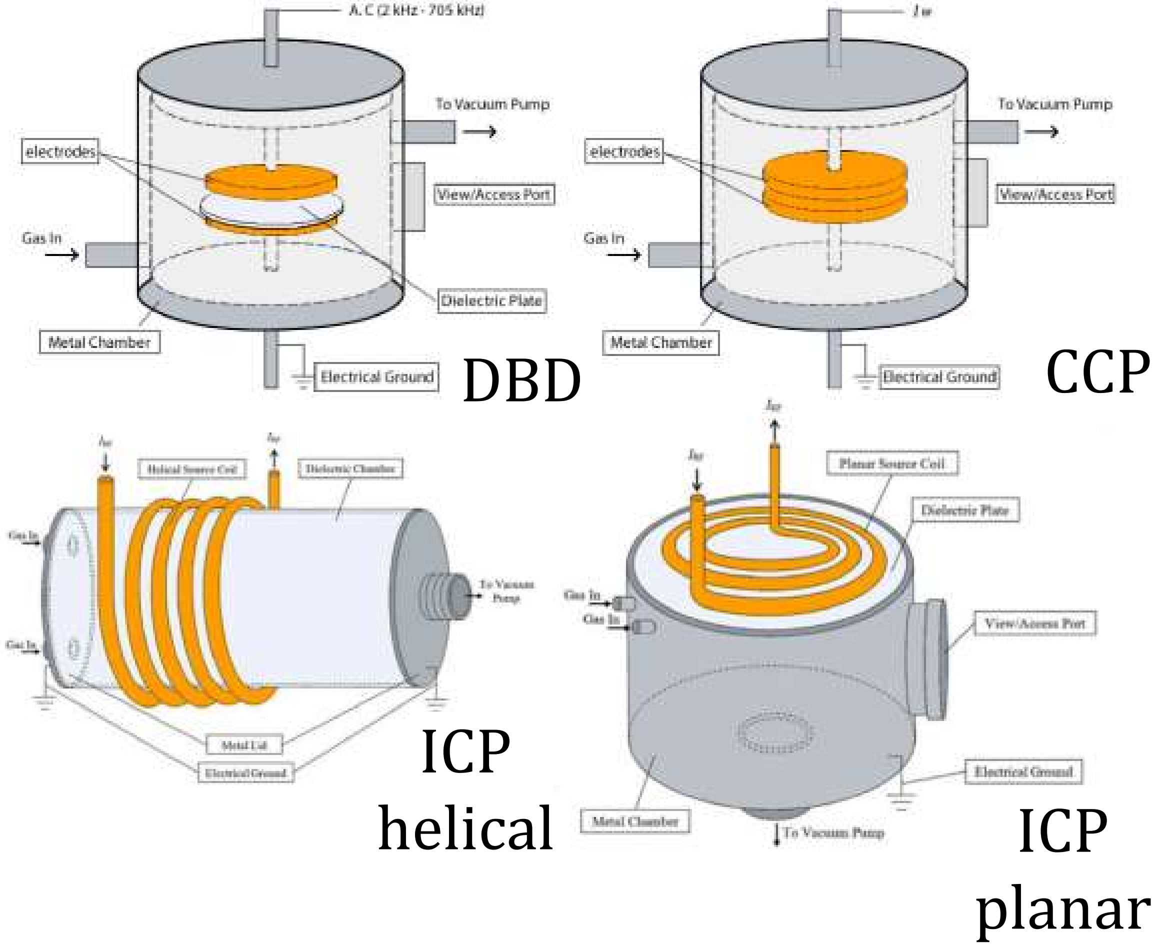
external $\vec{B}$

$$\overline{P_{\mathrm{tr}}} \sim \frac{q_e^2 E_0^2}{m_e}\left(\frac{f_{\mathrm{col}}}{f_{\mathrm{col}}^2 + \left(f_{\mu\mathrm{W}}^2 - f_{\mathrm{cycl}}^2\right)}\right)$$

$f_{\mathrm{cycl}} = f_{\mu\mathrm{W}} = 2.45\ \mathrm{GHz}$

for electrons and $B \doteq 88\ \mathrm{mT}$

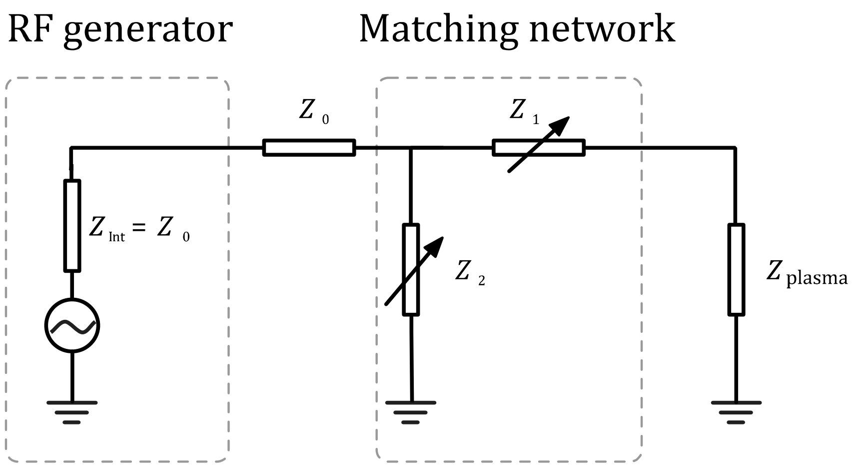
Capacitively or Inductively Coupled Plasma



Asadian M. et al. *Nanomaterials* 10 (2020) 119.
doi:10.3390/nano10010119

CCP or ICP

Dielectric-barrier discharge (DBD)



Bacelli G. et al. L-type Matching Network
doi: 10.5220/0001648802020207

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Conde, Luis. 2018. *An introduction to plasma physics and its space applications*. Volume 1, Fundamentals and elementary processes. San Rafael [California] (40 Oak Drive, San Rafael, CA, 94903, USA): Morgan & Claypool Publishers.
doi: 10.1088/2053-2571/aae132
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Boulos, M.I., Fauchais, P., Pfender, E. (2016). *Basic Concepts of Plasma Generation*. In: Handbook of Thermal Plasmas. Springer, Cham. doi: 10.1007/978-3-319-12183-3_11-1

Surzhikov, Sergey T. 2012. *Computational Physics of Electric Discharges in Gas Flows.* Vol. 7. Germany: De Gruyter.
doi: 10.1515/9783110270419
DC discharge