BASIC PLASMA CONCEPTS

GLOW DISCHARGE

ARC DISCHARGE

What is plasma?

Plasma is an electrically neutral medium of positive and negative particles that fulfills the following criteria:

1. The electron **plasma frequency** is large compared to the electron-neutral collision frequency. When this condition is valid, electrostatic interactions dominate over the processes of ordinary gas kinetics.

$$\tau_P << \tau$$

Plasma Frequency

$$E = \frac{enx}{\varepsilon_0}$$

The electrons move a distance *x* on the *E* field created by a background of *n* non-mobile ions

$$m_e \frac{dx^2}{dt^2} = -eE \Rightarrow \frac{dx^2}{dt^2} + \frac{ne^2}{\varepsilon_0 m_e} x = 0$$

$$x = x_0 \cos(\omega_P t + \delta)$$

ω^2

$$\omega_P = \sqrt{\frac{ne^2}{\varepsilon_0 m_e}}$$

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2. The **Debye screening length** is short compared to the physical size of the plasma. This criterion means that interactions in the bulk of the plasma are more important than those at its edges, where boundary effects may take place. When this criterion is satisfied, the plasma is quasi-neutral.

$$\lambda_D << L$$

Debye Length

λ_D is the scale over which mobile charge carriers screen out electric fields in plasmas and other conductors.
Within the λ_D quasineutrality DOES NOT apply.

1. We have equilibrium densities in the plasma of **n_i=n_e=n_0**

2. We "introduce" a sheet of negative charge, which repels the nearby electrons.

3. Near the sheet we have a reduced electron density, given by Boltzman´s relation

$$n_e(x) = n_0 e^{-e\Phi(x)/k_B T}$$

4. We consider ions non-mobile: $n_i = n_0$

$$\frac{d^2\Phi}{dx^2} = -\frac{e}{\varepsilon_0}(n_i - n_e) = -\frac{en_0}{\varepsilon_0}(e^{-e\Phi/k_B T} - 1)$$

$$\frac{d^2\Phi}{dx^2} \approx -\frac{en_0}{\varepsilon_0}\frac{e\Phi}{k_B T} \qquad \Rightarrow \Phi = \Phi_0 e^{-x/\lambda_D}$$

λ_D is therefore, the length for which the electric potential in a mixture of charges of different polarities falls to a value of 1/e.

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n_e e^2}}$$

Debye Length / plasma frequency

The distance traveled by a typical plasma particle during a plasma period:

$$l = v_{th} \cdot \tau_P = \sqrt{\frac{k_B T}{m_e}} \cdot \sqrt{\frac{\varepsilon_0 m_e}{n_e e^2}}$$

$$l \approx \lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n_e e^2}}$$

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3. Charged particles must be close enough together that each particle influences many nearby charged particles, rather than just interacting with the closest particle: **Collective behaviour** of the charged particles.

$$N_D = \frac{4\pi}{3} n \lambda_D^3 >> 1$$

Debye-Sphere

$$\frac{4\pi}{3}\lambda_D^3$$

Number of particles inside a Debye Sphere

$$N_D = \frac{4\pi}{3} n\lambda_D^3$$

Other plasma concepts

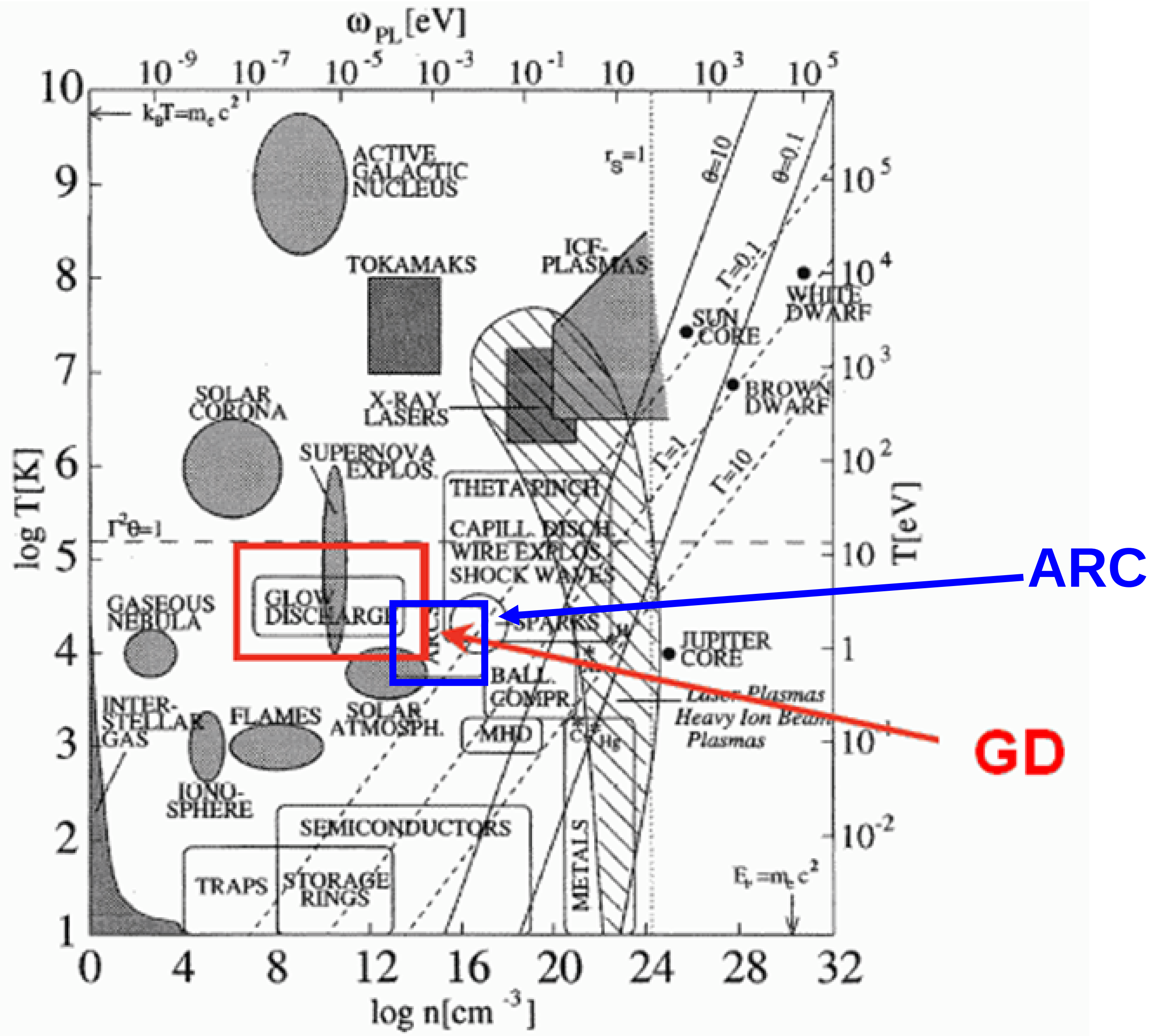
✓Plasma density (n_e, n_i, n)… and degree of ionization.

✓Energy distribution functions $\rightarrow$ Temperature

$$\langle E \rangle = \frac{\int \frac{1}{2} m v^2 f(v) d^3 v}{\int f(v) d^3 v} = \frac{3}{2} k_B T$$

Based in a combination of these two concepts, temperature and density, we can roughly classify our plasmas…

General classification of Plasmas



Concept of temperature / equilibrium

Classification of plasmas according to thermodynamic equilibrium:

•Plasmas in complete thermodynamic equilibrium: We do not find them in the lab

High pressures

•Plasmas in LTE.

These plasmas require one of these two conditions:

- High pressures: **Arc** (10-100Torr or more)
- When the heavy particles are very energetic (T ~ 10^6 – 10^8K) such as in controlled thermonuclear fusion

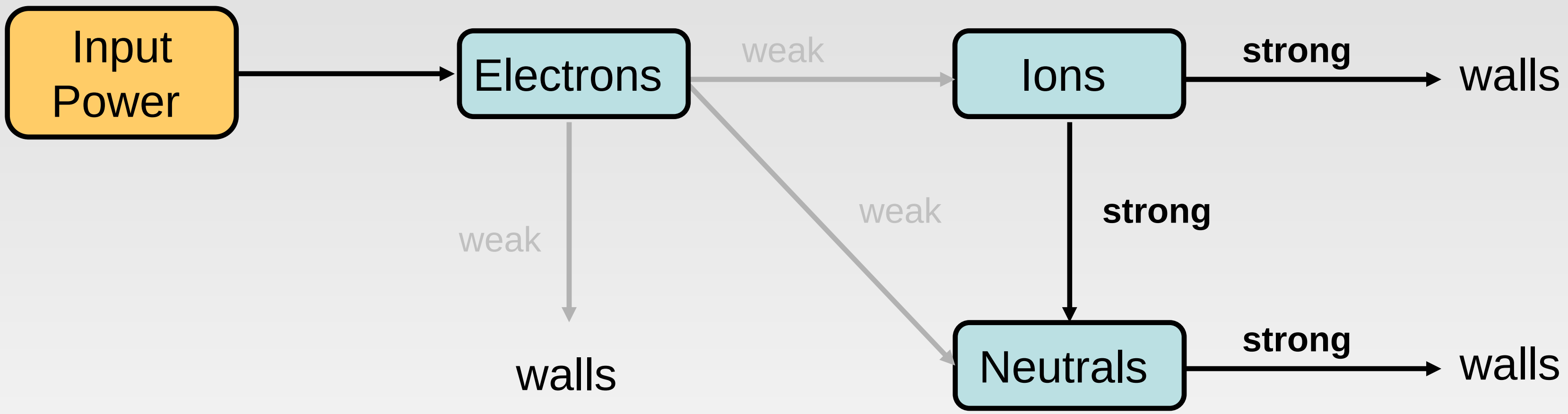
•Plasmas in non-LTE: At pressures below 0.1 atm and currents around 1A the plasma is usually never in equilibrium. **Glow** Discharge

Low pressures

Temperatures in glow discharge: non LTE

Why the disparity in temperatures?

Low pressures



The electrons gain more energy from the electric field (*E*) than the ions

$$W = \frac{(Eet)^2}{2m}$$

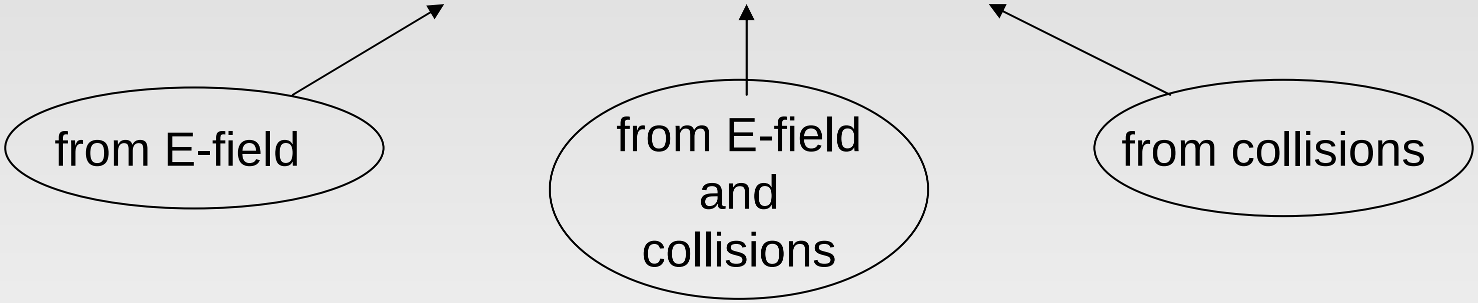
Electrons are not in equilibrium with ions or neutrals because the elastic energy transfer between electrons and ions or neutrals is very ineffective

$$Max.Transf.Energy = \frac{4m_i m_e}{(m_i + m_e)^2}$$

$T_e >> T_i, T_n$ in the plasma bulk

Some numbers

Species present in the plasma, ordered according to temperature:
electrons >> ions > neutrals

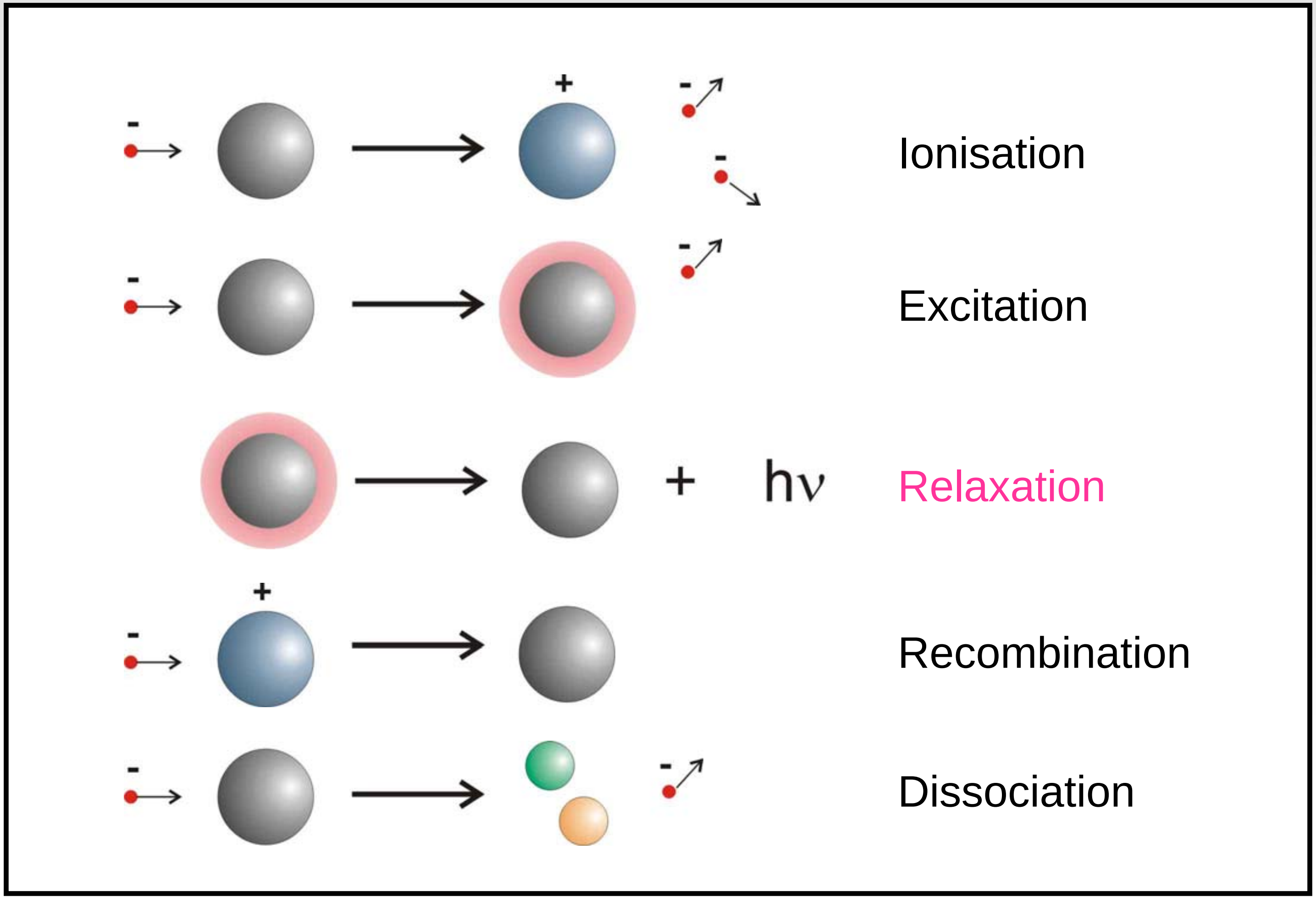


Typical Argon plasma	Mass (Kg)	Temperature (K)	Velocity (m/s)
Neutrals	$6.7 \cdot 10^{-26}$	300	400
Ions	$6.7 \cdot 10^{-26}$	500	500
Electrons	$9.1 \cdot 10^{-31}$	23200	950000

Electron collision processes

Due to mass difference, almost no energy transfer in elastic collisions (0.01%)

Energy transfer happens through inelastic collisions (99.99%)



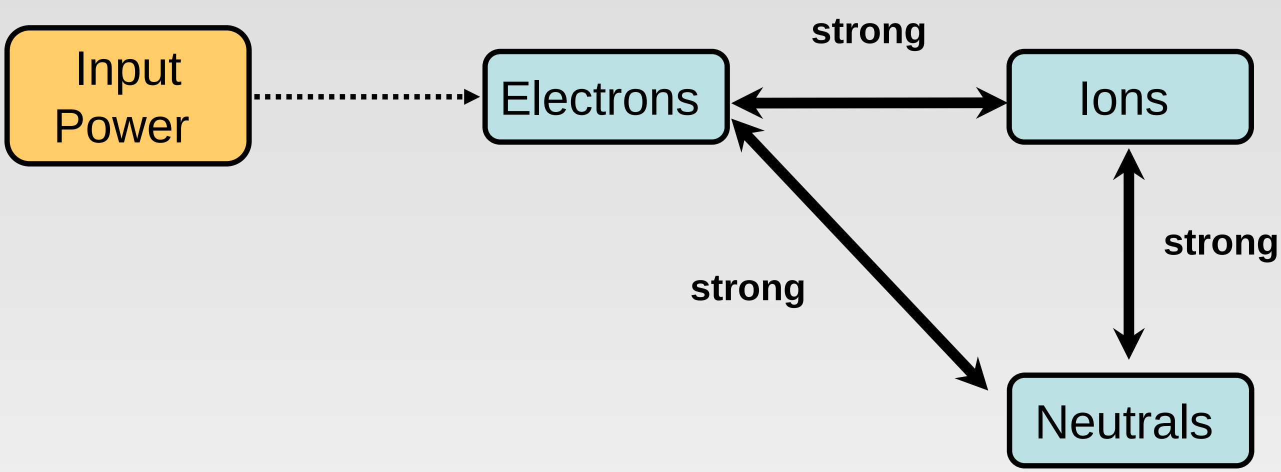
Temperatures in glow discharge: non LTE

$T_e >> T_i, T_n$ in the plasma bulk

We manage **high temperature processing at low temperatures**:

1. The surfaces in contact with the plasma are near room temperature
2. Electrons produce free radicals $\rightarrow$ chemistry
3. Electrons can produce e-ion pairs $\rightarrow$ ion bombardment

Temperatures in arc discharge: LTE



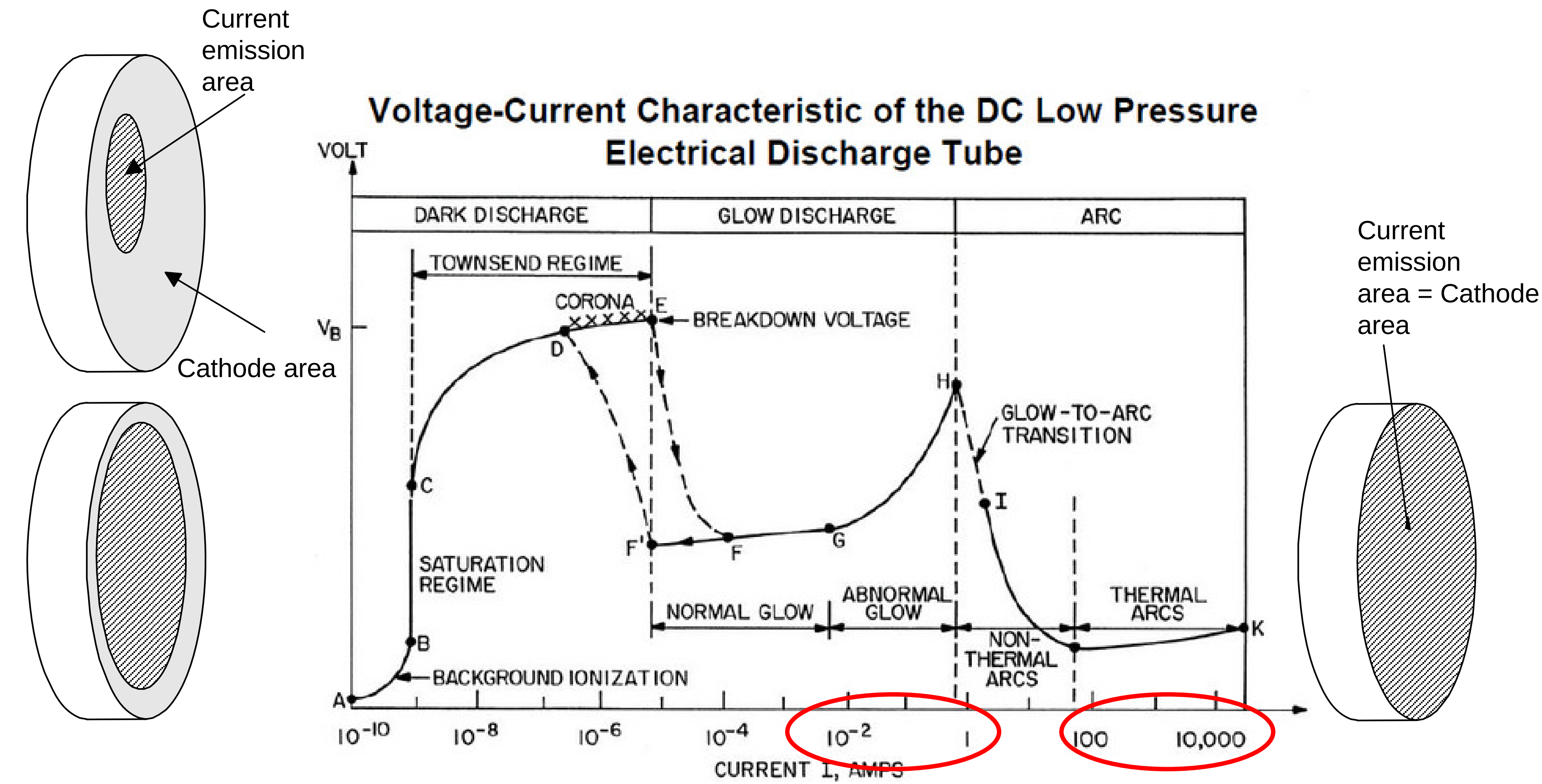
High pressures
High Current

The equilibration of temperatures is caused by intensive energy exchange between electrons and molecules through excitation of vibrations and rotations and by large scattering cross sections of electrons in **metal vapor**. Interchange is BILATERAL.

The main mechanism from which the electrons gain energy in this case is not through the electric field. The field pumps energy into the electron gas as a whole, but electrons are thermalized through collisions with other electrons. The gas is ionized by those electrons that acquired sufficiently energy, not from the field, but in the exchange with other particles. Thermal ionization proceeds then *independently* of the way in which we pump energy into the plasma.

$T_e \sim T_i$, T_n in the plasma bulk

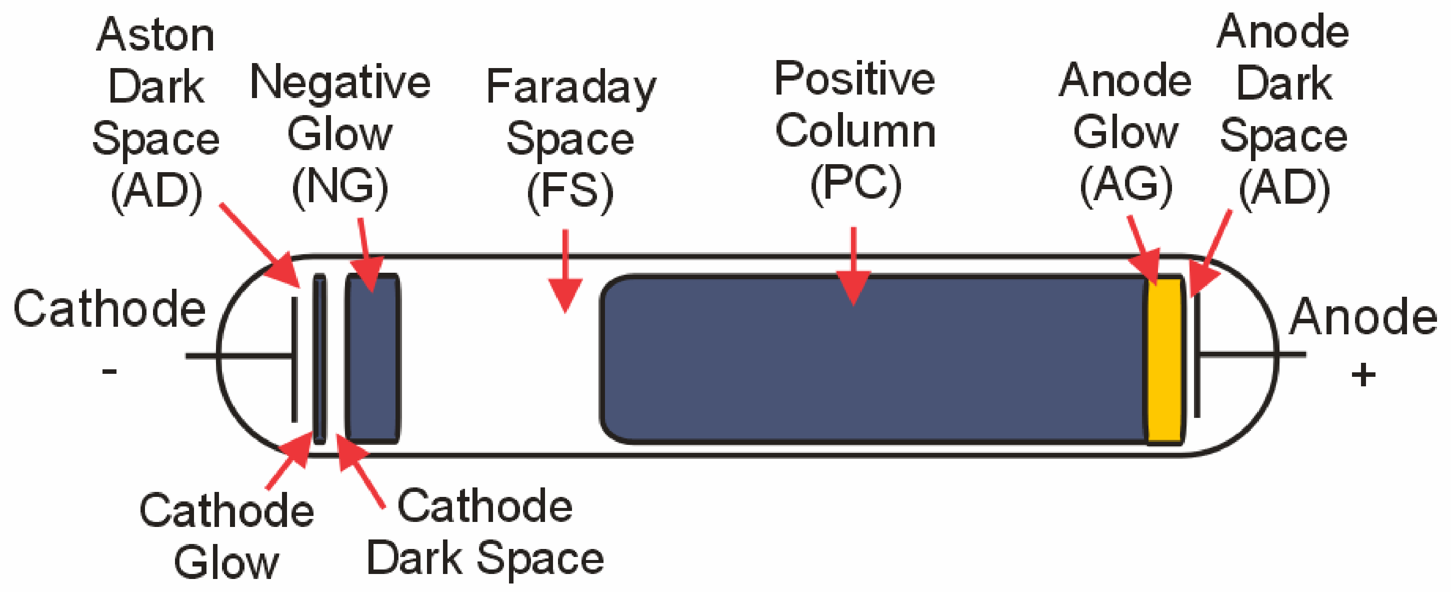
Voltage-current charcateristics: from Glow to Arc



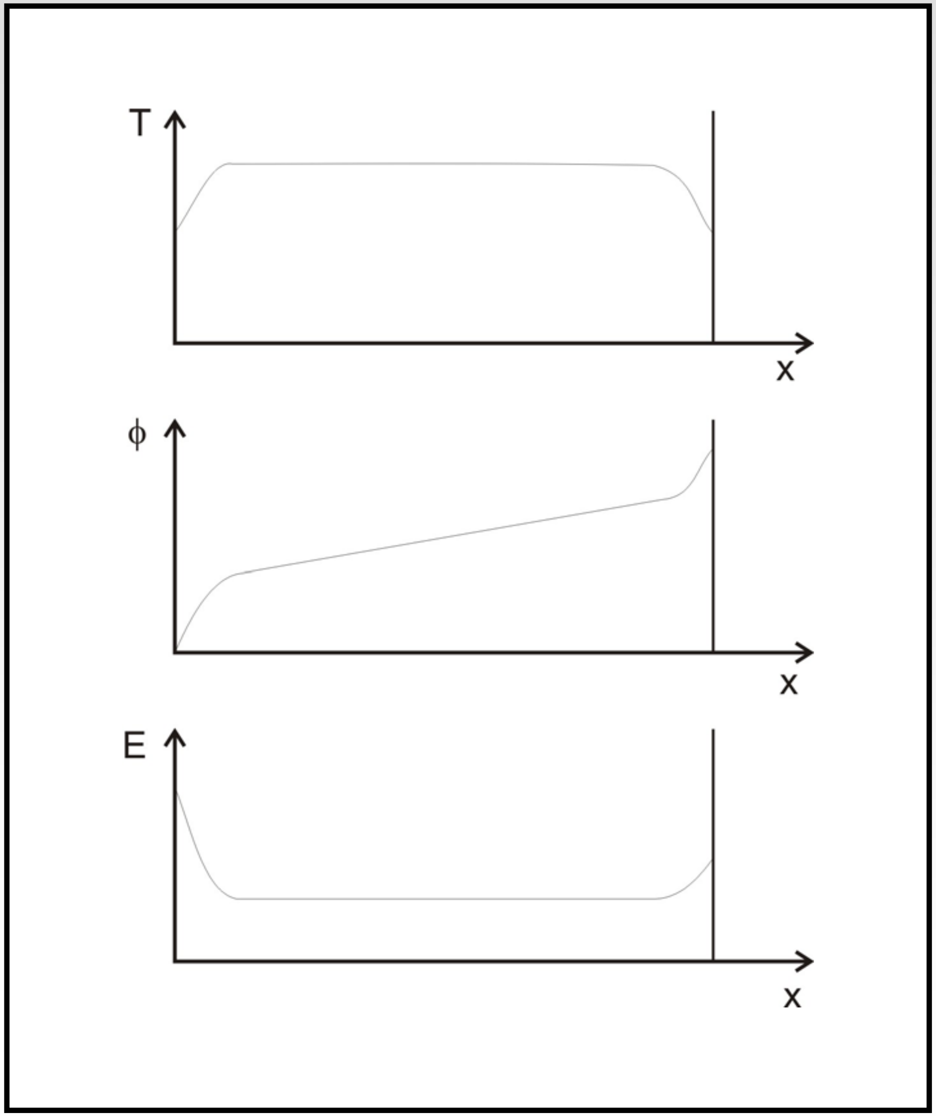
J. R. Roth (1995): Industrial Plasma Engineering

An electric arc has a non-linear relationship between current and voltage. Once the arc is established increased current results in a lower voltage between the arc terminals. This negative resistance effect requires that some positive form of impedance to be placed in the circuit, if it is desired to maintain a stable arc. This property is the reason uncontrolled electrical arcs in apparatus become so destructive, since once initiated an arc will draw more and more current from a fixed-voltage supply until the apparatus is destroyed.

Anatomy of a glow Discharge



Anatomy of an arc Discharge



Main characteristic of the arc cathode layer is a high current density.

Electron production in glow discharge

The electrons needed to sustain the discharge are produced by:

Secondary electron emission: incident ions of sufficient energy induce electron emission by impact against the cathode

AND

Through production of ion/electron pairs by **collisions** in the gas phase. The electrons gain the energy necessary for ionization in the cathode fall.

In glow discharges, ion bombardment provides electrons through secondary emission

Electron production in arc discharge

Thermionic emission: heat-induced flow of charge carriers from a surface or over a potential-energy barrier. This occurs because the thermal energy given to the carrier overcomes the forces restraining it.

Field electron emission: emission of electrons induced by external electromagnetic fields. Field emission is explained by quantum tunneling of electrons.

Thermionic field emission: in electron emission devices, especially electron guns, the thermionic electron emitter will be biased negative relative to its surroundings. This creates an electric field the emitter surface. Without the field, the surface barrier seen by an escaping Fermi-level electron has height to the local work-function. The electric field lowers the surface barrier and increases the emission current. This is known as the "Schottky effect´´ or field enhanced thermionic emission.

In arc discharges, ion bombardment provides cathode heating, which then leads to the escape of electrons from the surface.

Comparison Arc / Glow

	Cathode fall	Ionic current in the cathode $1-S=\frac{1}{\gamma+1}$	Electronic current in the cathode $S=\frac{\gamma}{\gamma+1}$	Electrons per ion γ
GLOW	**Hundreds volts**	≤ 1	$\approx 0.001-0.1$	$\approx 0.001-0.1$ **Secondary** emission mechanism
ARC	**10V**	$\approx 0.1-0.3$	$\approx 0.7-0.9$	$\approx 2-9$ **Thermionic** emission mechanism