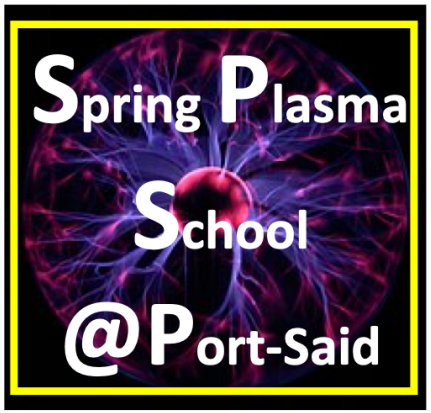
Plasma Theory

Ibrahem Elkamash, PhD

Physics Department, Faculty of Science, Mansoura University, 35516 Mansoura, Egypt

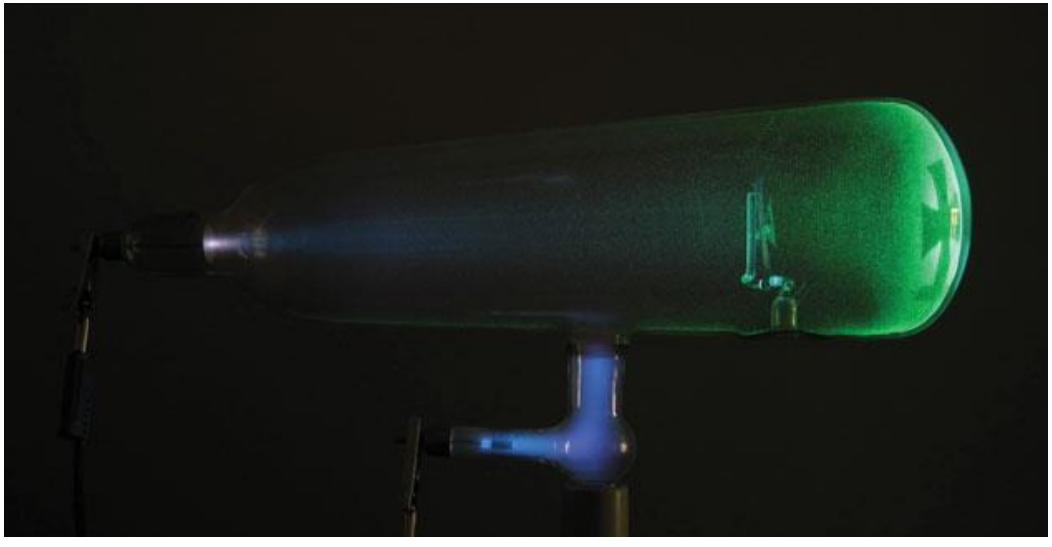
7^{th} Spring Plasma School at PortSaid (SPSP2022), PortSaid, Egypt.



March 6, 2022

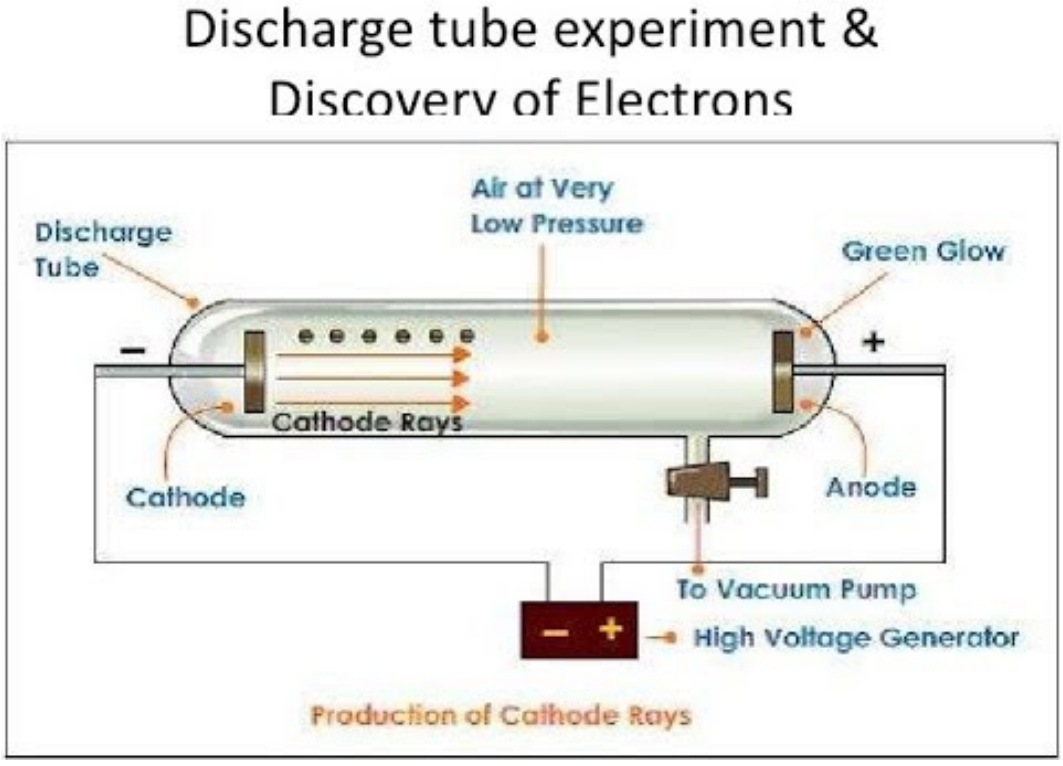
Plasma History

- 1897: Sir William Crookes identified the plasmas in a discharge tube (or Crookes tube), he called it “radiant matter”.



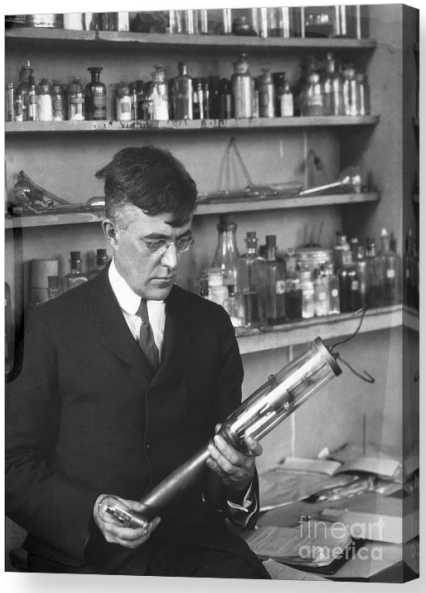
Plasma History

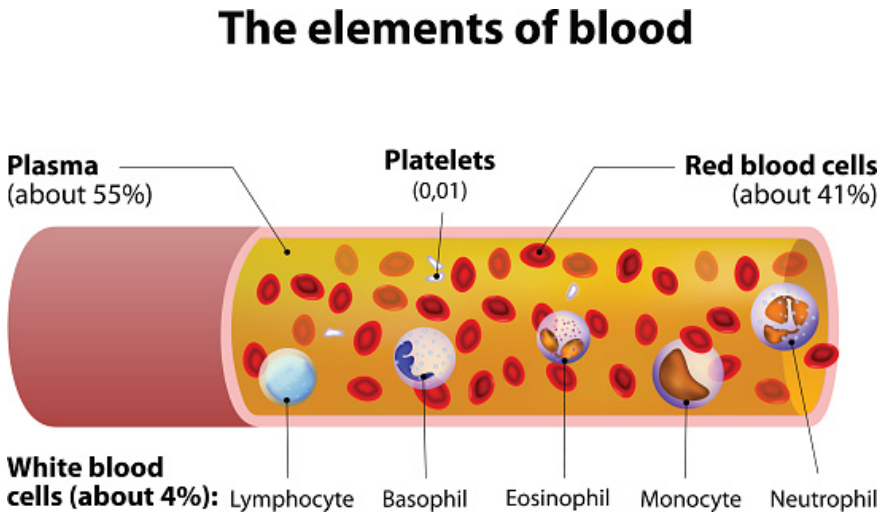
- 1897: Sir J.J. Thomson (Nobel Prize in Physics (1906)) identified the nature of the Crookes tube "cathode ray" matter and proved that the cathode rays consist of streams of negative electrons.



Plasma History

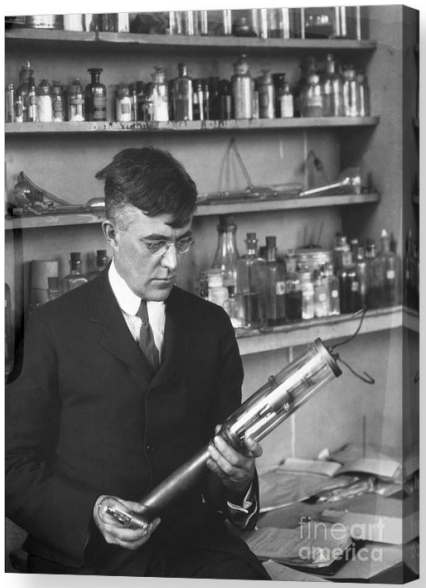
- 1924: Irving Langmuir (Nobel Prize in Chemistry 1932) coined for the first time the terms “plasma”, perhaps because it reminded him of a blood plasma.

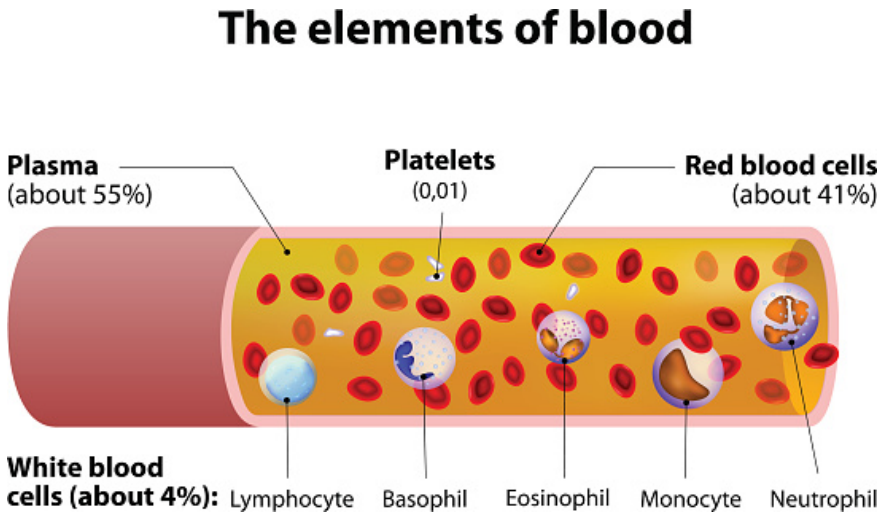




Plasma History

- 1924: Irving Langmuir (Nobel Prize in Chemistry 1932) coined for the first time the terms "plasma", perhaps because it reminded him of a blood plasma.

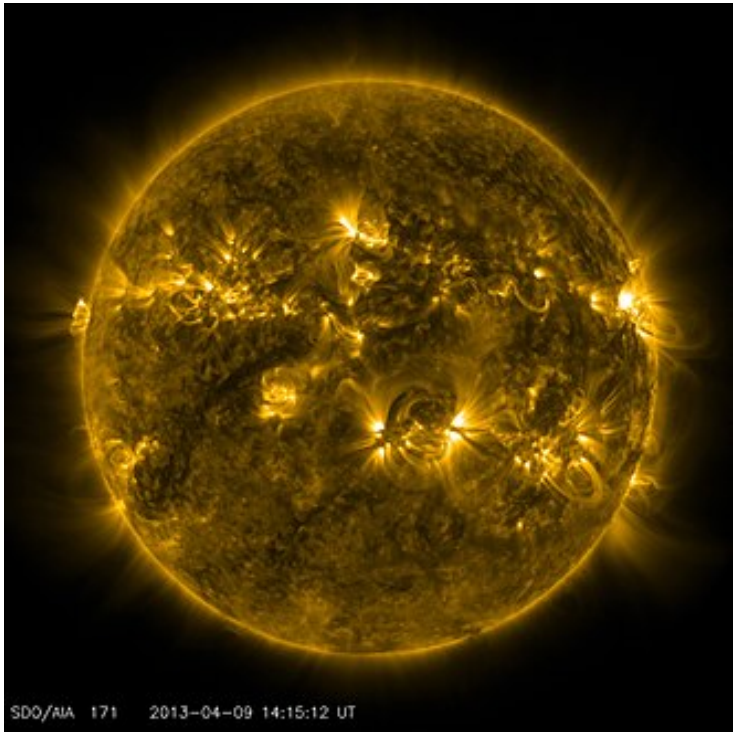




- Langmuir wrote: *"Except near the electrodes, where there are sheaths containing very few electrons, the ionized gas contains ions and electrons in about equal numbers so that the resultant space charge is very small. We shall use the name* **"plasma"** *to describe this region containing balanced charges of ions and electrons."*

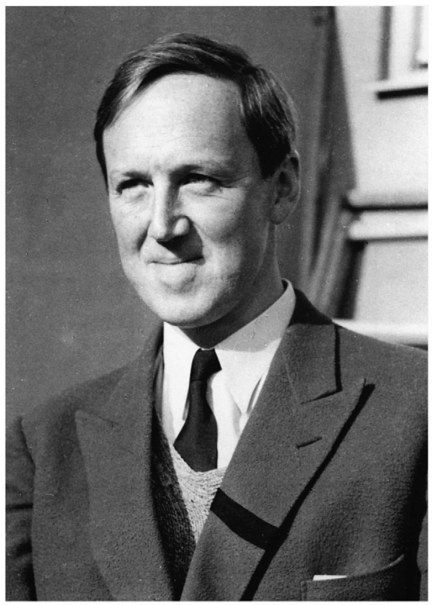
Plasma History

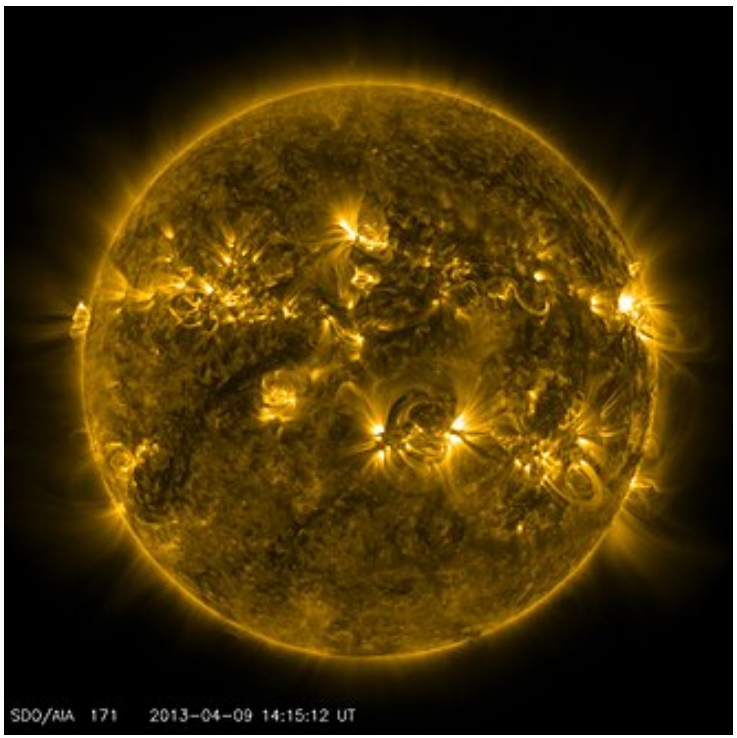
- In 1942: Hannes Alfvén (Nobel Prize in Physics1970), developed the theory of magnetohydrodyamics, or MHD, in which plasma is treated essentially as a conducting fluid.



Plasma History

- In 1942: Hannes Alfvén (Nobel Prize in Physics1970), developed the theory of magnetohydrodyamics, or MHD, in which plasma is treated essentially as a conducting fluid.

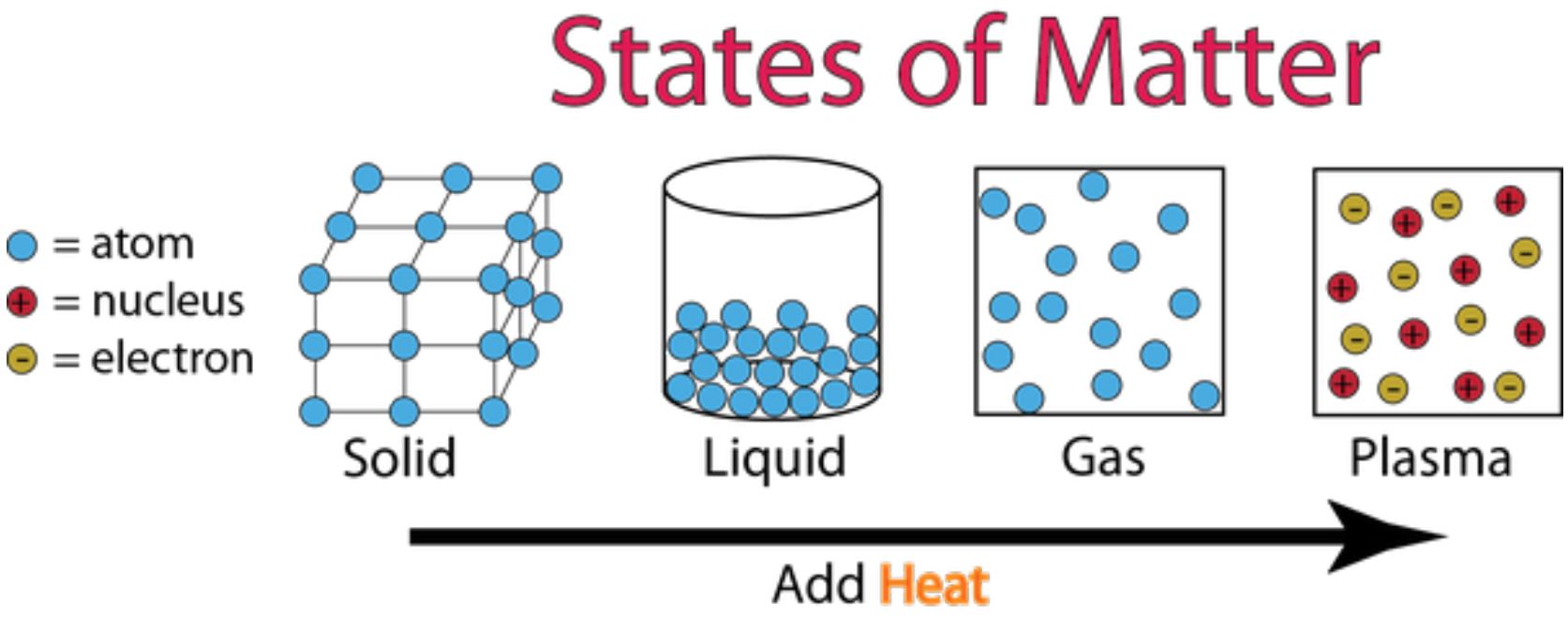




- Alfven wrote: *"At last some remarks are made about the transfer of momentum from the Sun to the planets, which is fundamental to the theory. The importance of the* **magnetohydrodynamic** *waves in this respect are pointed out."*

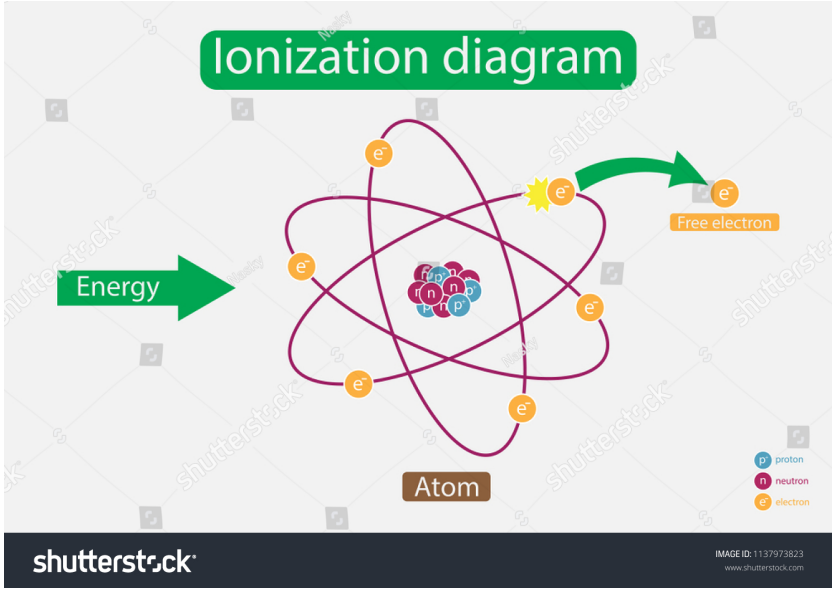
Plasma Definition

- Plasma: is a **State** of matter which is **Ionized**, **Quasineutral** and exhibits **Collective Behavior**.



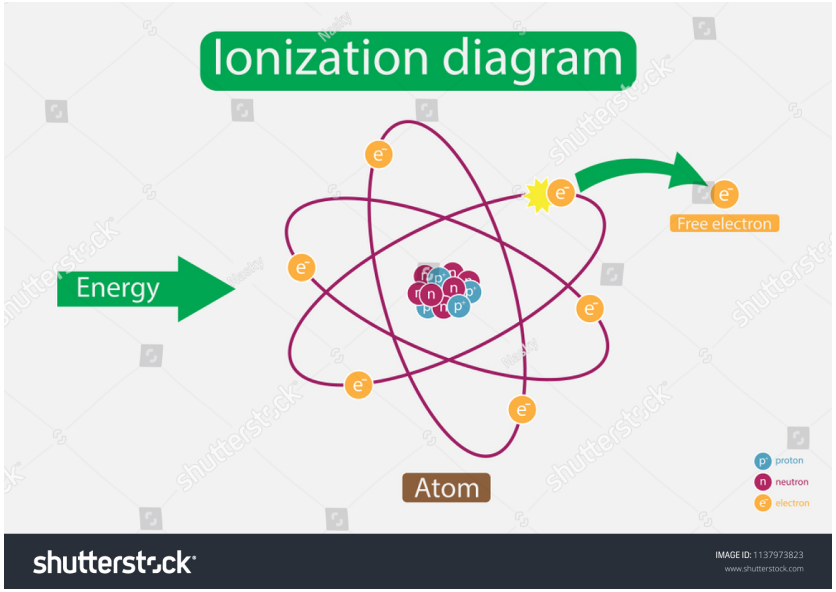
Plasma Definition: Ionization

- Ionization: is the process by which an atom or a molecule acquires a negative or positive charge by gaining or losing electrons.



Plasma Definition: Ionization

- Ionization: is the process by which an atom or a molecule acquires a negative or positive charge by gaining or losing electrons.



- The degree of ionization (the Saha equation):

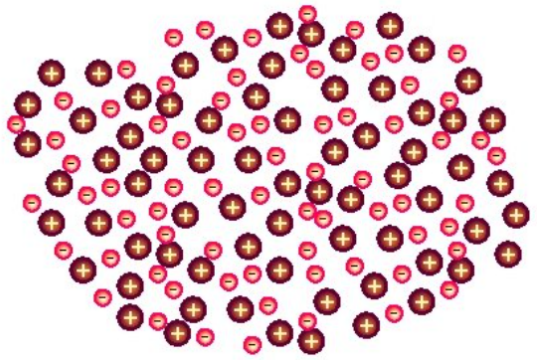
$$r = \frac{N_e}{N_i + N_n} \approx 2.4 \times 10^{21} e^{-\frac{\Phi}{K_B T}}$$

i.e. $r = 1$: Complete ionization; $r < 1$: Partial ionization.

e.g. Air: $r \sim 10^{-122}$; F-layer of Ionosphere: $r \sim 10^{-4}$.

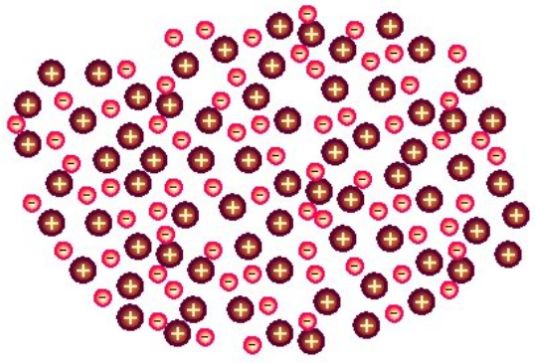
Plasma Definition: Quasineutral

- Quasineutral: nearly equal number of oppositely charged particles.



Plasma Definition: Quasineutral

- Quasineutral: nearly equal number of oppositely charged particles.



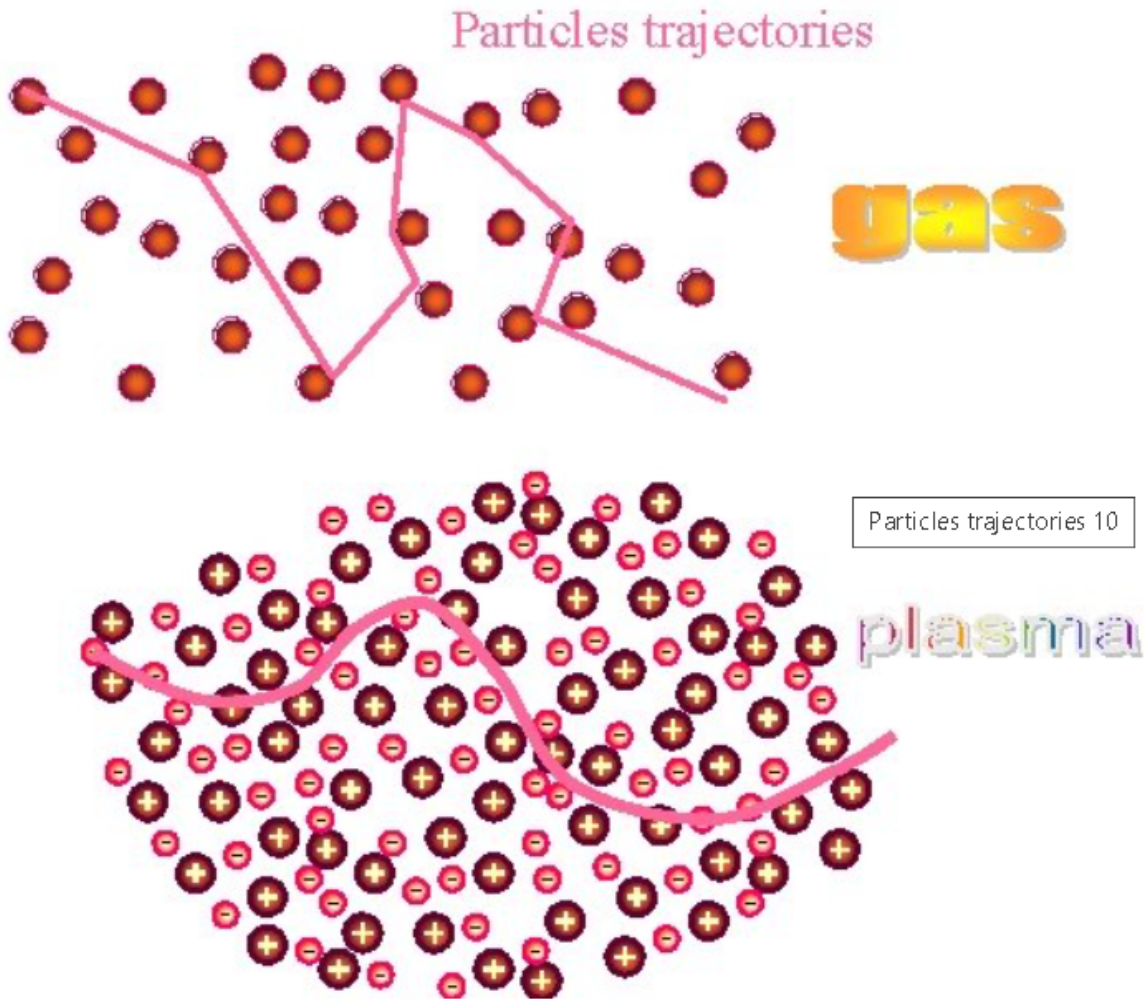
$$E \approx 0 \qquad \rightarrow \qquad \rho_+ \approx \rho_-,$$

i.e.

$$q_+ n_+ \approx q_- n_-.$$

Plasma Definition: Collective Behavior

- Collective behavior: motions that depend not only on local conditions but on the state of the plasma in remote regions as well.



Plasma Characteristics: Debye shielding

- Debye length: is the distance over which the electric field of a charged particle is felt by other charged particles in a plasma.

$$\frac{d^2\phi}{dx^2} - \frac{1}{\lambda_D^2}\phi = \frac{Q}{\epsilon_0}\delta(x - x_0),$$

The solution is: $\phi = \frac{Q}{4\pi\epsilon_0 x^2} e^{-\frac{x}{\lambda_D}}$,

where $\lambda_D = \left(\frac{K_B T_e}{4\pi n_0 e^2}\right)^{1/2} = 7.43 \times 10^2 \left(T_e/n_0\right)^{1/2}$ cm, T_e (eV) and $n_0(\mathrm{cm}^{-3})$.

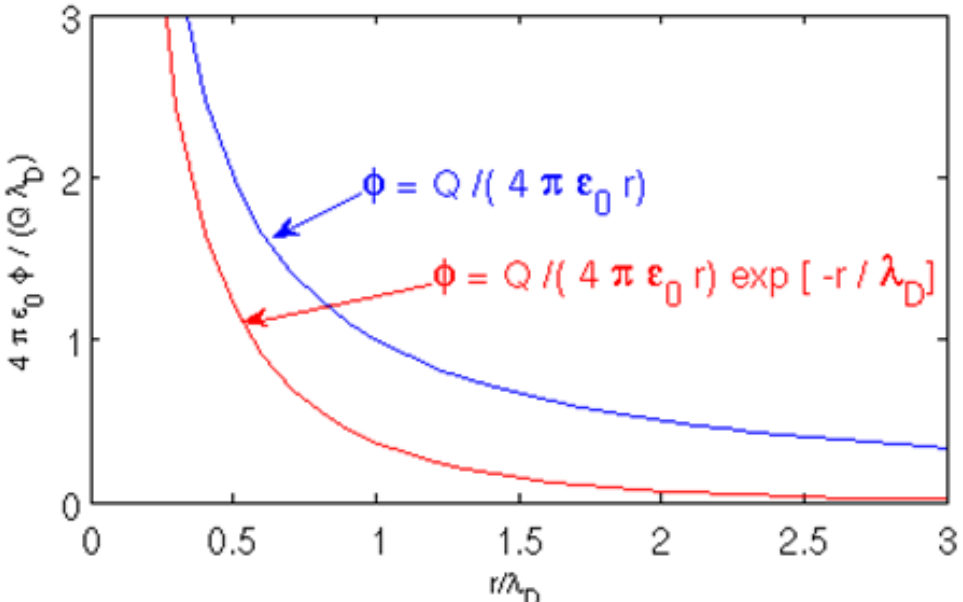
Plasma Characteristics: Debye shielding

- Debye length: is the distance over which the electric field of a charged particle is felt by other charged particles in a plasma.

$$\frac{d^2\phi}{dx^2} - \frac{1}{\lambda_D^2}\phi = \frac{Q}{\epsilon_0}\delta(x - x_0),$$

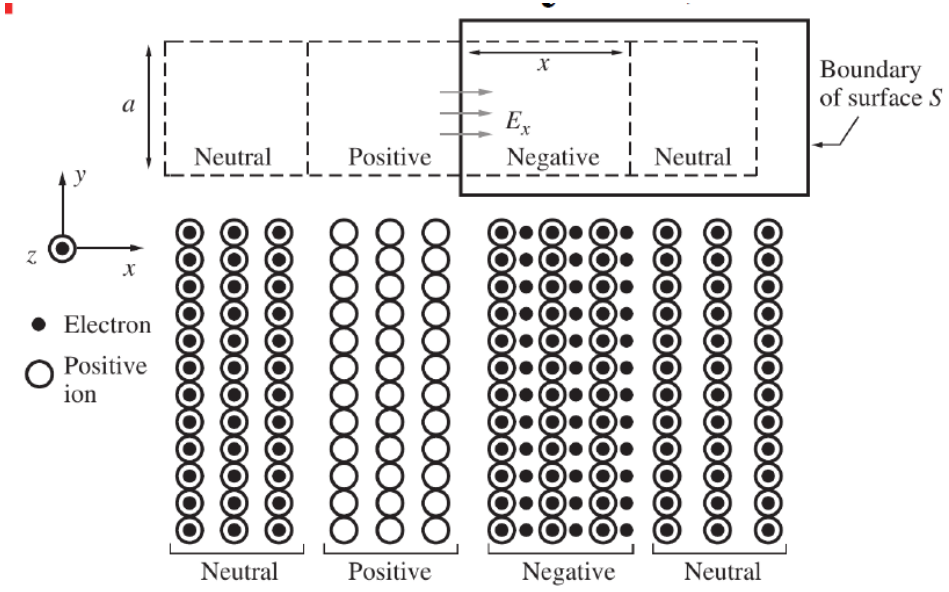
The solution is: $\phi = \frac{Q}{4\pi\epsilon_0 x^2} e^{-\frac{x}{\lambda_D}}$,

where $\lambda_D = \left(\frac{K_B T_e}{4\pi n_0 e^2}\right)^{1/2} = 7.43 \times 10^2 \left(T_e/n_0\right)^{1/2}$ cm, T_e (eV) and $n_0(\mathrm{cm}^{-3})$.



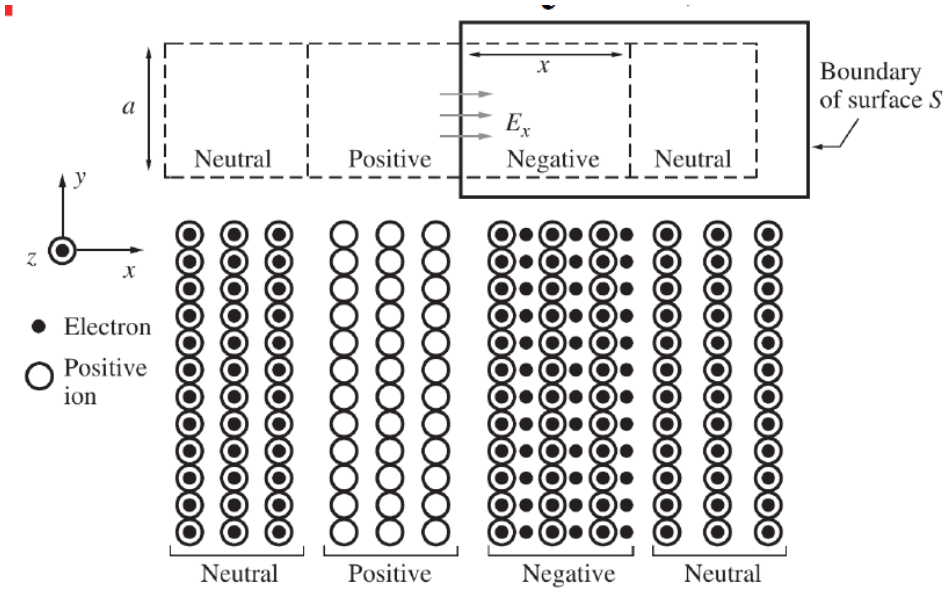
Plasma Characteristics: Plasma Frequency

- Plasma Frequency: the natural response frequency to the perturbation.



Plasma Characteristics: Plasma Frequency

- Plasma Frequency: the natural response frequency to the perturbation.



$$\frac{d^2n}{dt^2} + \omega_p^2 n = 0,$$

The solution is: $n = n_0 \cos(\omega_p t)$.

where $\omega_p = (\frac{4\pi n_0 e^2}{m_e})^{1/2} = 5.64 \times 10^4 n_0^{1/2} \mathrm{rad/sec}$, n_0 (cm^{-3}).

- Note that: $\omega_p^{-1} = \tau_p = \frac{\lambda_D}{V_{th}}$, τ_p: plasma time response.

Plasma Characteristics: Coupling Parameter

- Coupling (plasma) parameter: describe the individual vs. the collective behaviour.

$$\Gamma_C = \frac{E_C}{E_{th}} = \frac{e^2/4\pi\epsilon_0 d}{K_B T} \approx \frac{1}{n_d \frac{4\pi}{3}\lambda_D^3} \approx \frac{1}{N_D}.$$

- Where E_C: the Coulomb potential energy.

  E_{th}: the thermal energy.

  $d = (\frac{4\pi}{3} n_d)^{-1/3}$: the mean inter-particle distance.

Plasma Characteristics: Collision Frequency

- Collision Frequency: describes the rate of collisions between two atomic or molecular species in a given volume, per unit time.

$$\nu \sim \frac{\ln \Gamma_c}{\Gamma_c} \omega_p,$$

- $$\frac{d^2 n}{dt^2} + \nu \frac{dn}{dt} + \omega_p^2 n = 0,$$

The solution for $\nu \ll \omega_p$ is: $n = n_0 e^{-\frac{\nu}{2} t} \cos(\omega_p t)$.

Plasma Conditions

- The Quasineutrality condition:

$$\lambda_D \ll L$$

Plasma Conditions

- The Quasineutrality condition:

$$\lambda_D \ll L$$

- The Collective Behaviour condition:

$$Nd(= n_d \lambda_D^3) \gg 1$$

Plasma Conditions

- The Quasineutrality condition:

$$\lambda_D \ll L$$

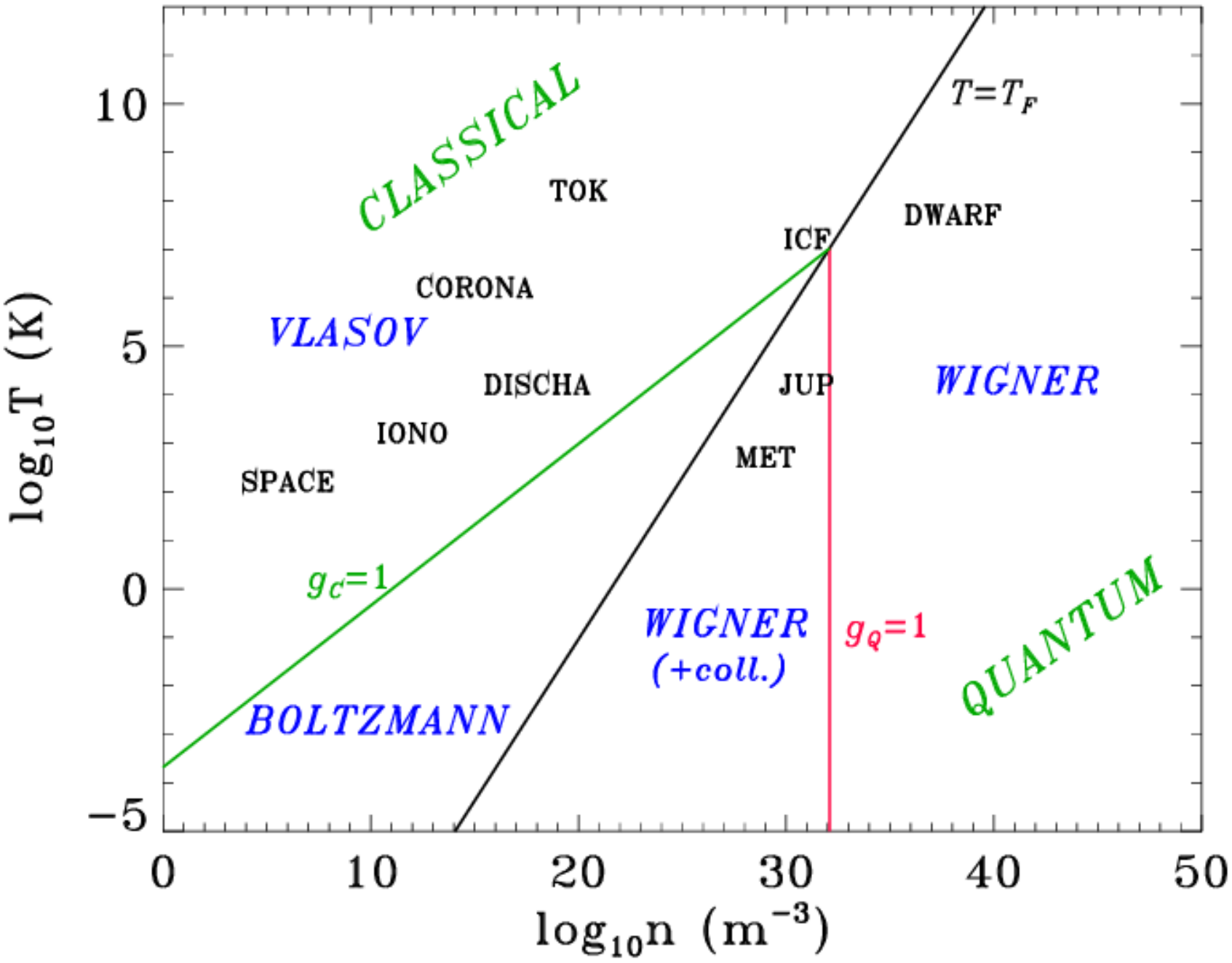
- The Collective Behaviour condition:

$$Nd(= n_d \lambda_D^3) \gg 1$$

- The Weakly Coupled (Collision) condition:

$$\omega_p \gg \nu$$

Plasma Characteristics



Plasma Classification

- Scale: Laboratory, Space, Astrophysics, Cosmological.

Plasma Classification

- Scale: Laboratory, Space, Astrophysics, Cosmological.
- Ionization: Partially (Weakly), Fully (Complete).

Plasma Classification

- Scale: Laboratory, Space, Astrophysics, Cosmological.
- Ionization: Partially (Weakly), Fully (Complete).
- Temperature: Cold, Warm, Hot.

Plasma Classification

- Scale: Laboratory, Space, Astrophysics, Cosmological.
- Ionization: Partially (Weakly), Fully (Complete).
- Temperature: Cold, Warm, Hot.
- Density: Low, High.

Plasma Classification

- Scale: Laboratory, Space, Astrophysics, Cosmological.
- Ionization: Partially (Weakly), Fully (Complete).
- Temperature: Cold, Warm, Hot.
- Density: Low, High.
- Collisions: Collisional (Non-Ideal), Collisionless (Ideal).

Plasma Classification

- Scale: Laboratory, Space, Astrophysics, Cosmological.
- Ionization: Partially (Weakly), Fully (Complete).
- Temperature: Cold, Warm, Hot.
- Density: Low, High.
- Collisions: Collisional (Non-Ideal), Collisionless (Ideal).
- Magnetic: Unmagnetized, Magnetized.

Plasma Classification

- Scale: Laboratory, Space, Astrophysics, Cosmological.
- Ionization: Partially (Weakly), Fully (Complete).
- Temperature: Cold, Warm, Hot.
- Density: Low, High.
- Collisions: Collisional (Non-Ideal), Collisionless (Ideal).
- Magnetic: Unmagnetized, Magnetized.
- Relativity: Non-Relativistic, Relativistic.

Plasma Classification

- Scale: Laboratory, Space, Astrophysics, Cosmological.
- Ionization: Partially (Weakly), Fully (Complete).
- Temperature: Cold, Warm, Hot.
- Density: Low, High.
- Collisions: Collisional (Non-Ideal), Collisionless (Ideal).
- Magnetic: Unmagnetized, Magnetized.
- Relativity: Non-Relativistic, Relativistic.
- Quantum: Classical, Quantum.

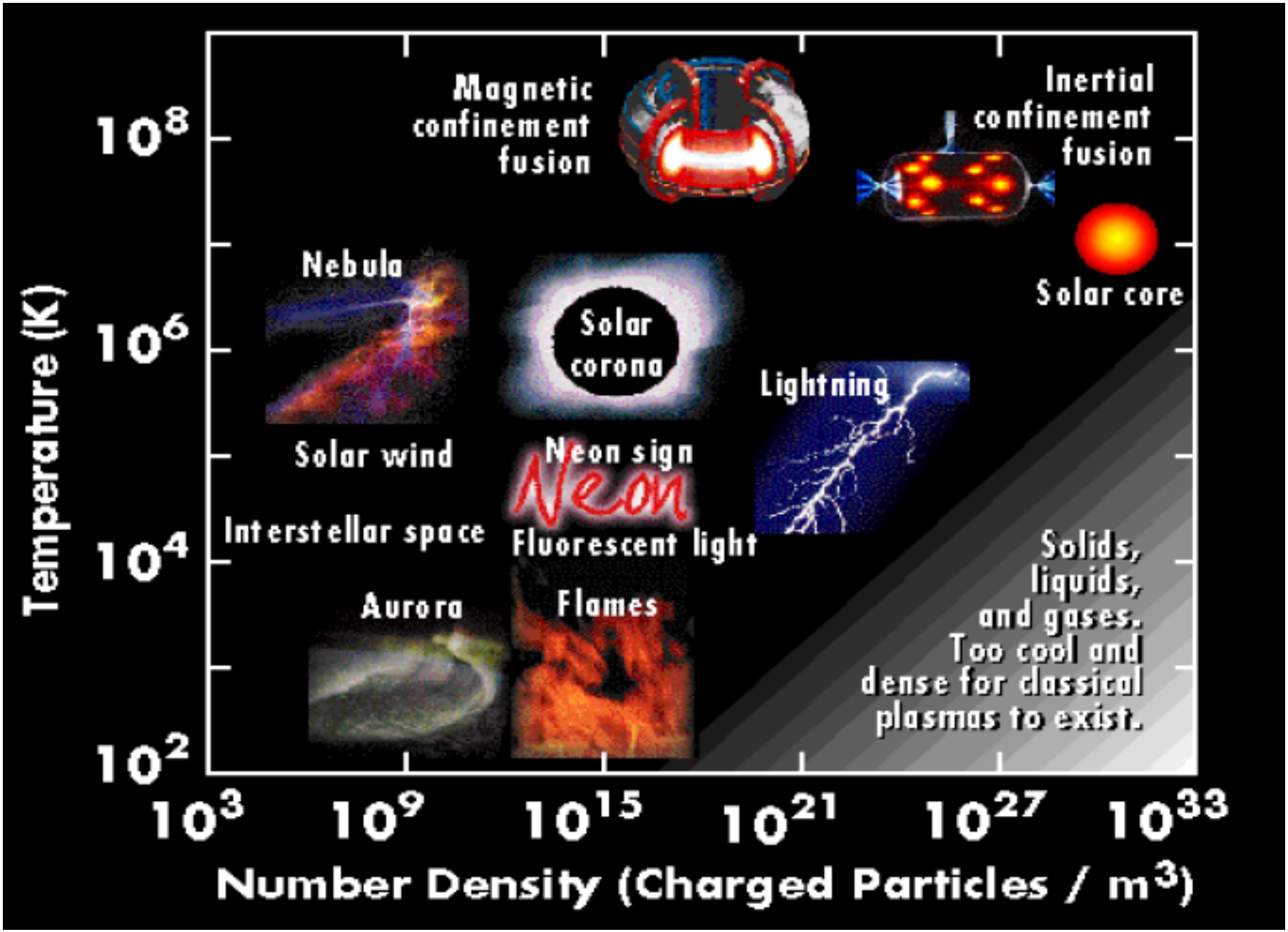
Plasma Classification

- Scale: Laboratory, Space, Astrophysics, Cosmological.
- Ionization: Partially (Weakly), Fully (Complete).
- Temperature: Cold, Warm, Hot.
- Density: Low, High.
- Collisions: Collisional (Non-Ideal), Collisionless (Ideal).
- Magnetic: Unmagnetized, Magnetized.
- Relativity: Non-Relativistic, Relativistic.
- Quantum: Classical, Quantum.
- Coupling: Weakly, strongly.

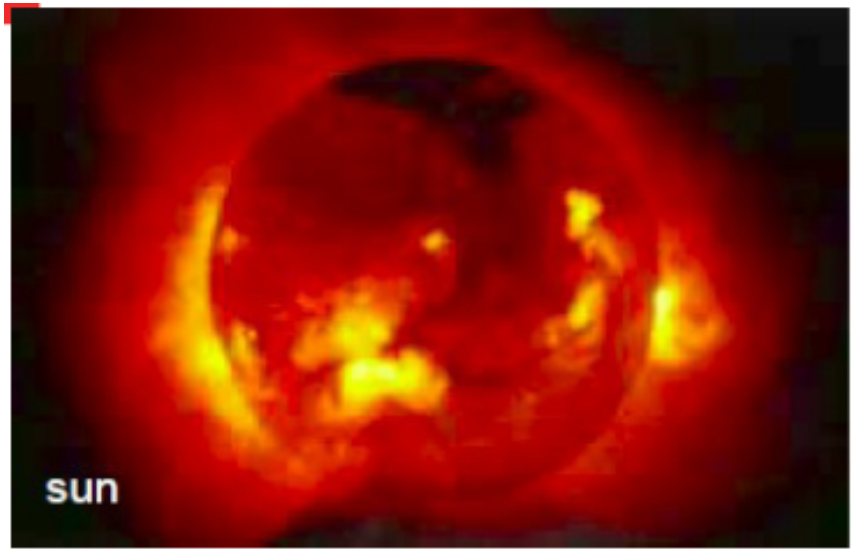
Plasma Classification

- Scale: Laboratory, Space, Astrophysics, Cosmological.
- Ionization: Partially (Weakly), Fully (Complete).
- Temperature: Cold, Warm, Hot.
- Density: Low, High.
- Collisions: Collisional (Non-Ideal), Collisionless (Ideal).
- Magnetic: Unmagnetized, Magnetized.
- Relativity: Non-Relativistic, Relativistic.
- Quantum: Classical, Quantum.
- Coupling: Weakly, strongly.
- Complexity: Dusty, Classical.

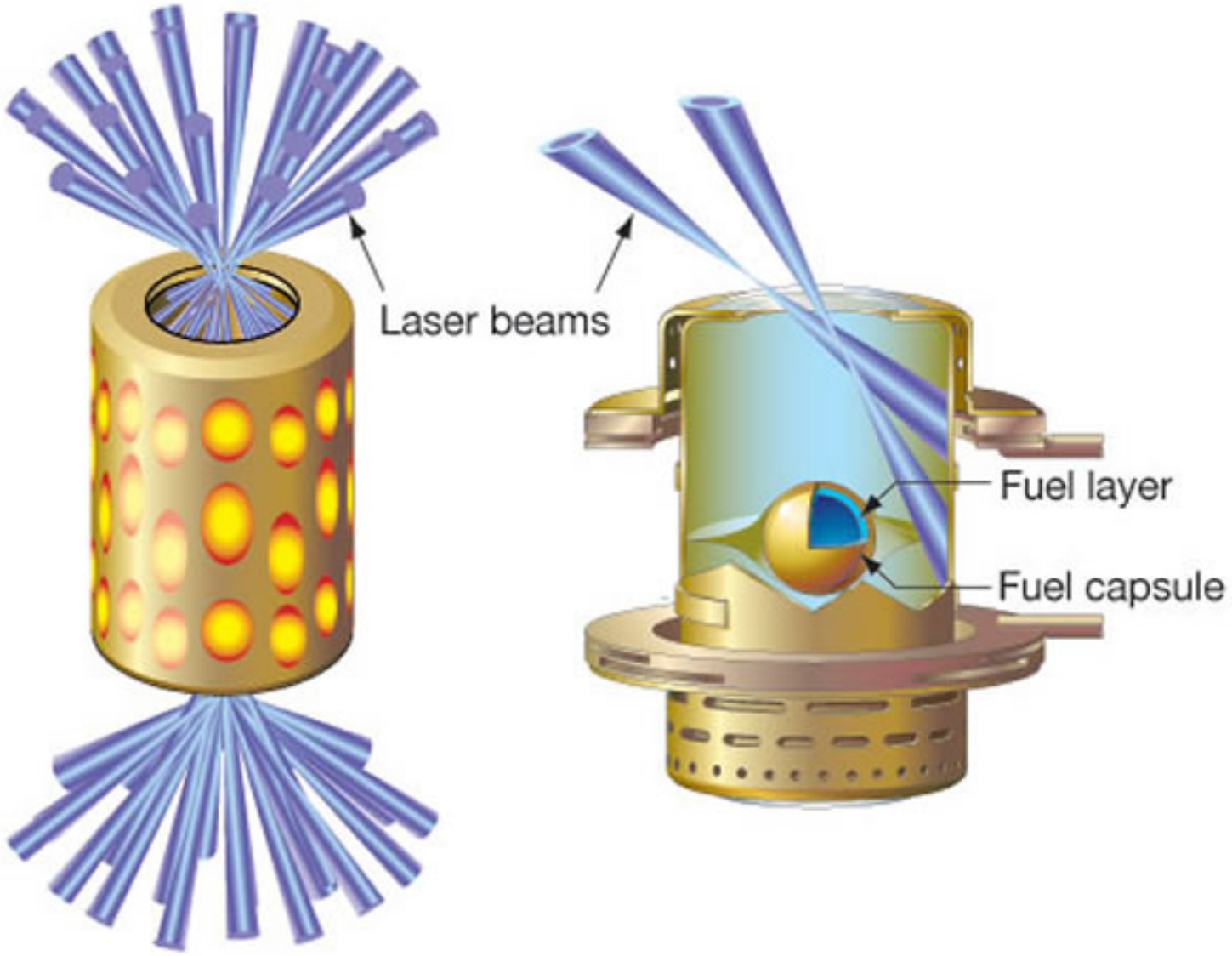
Plasma Applications: Universe



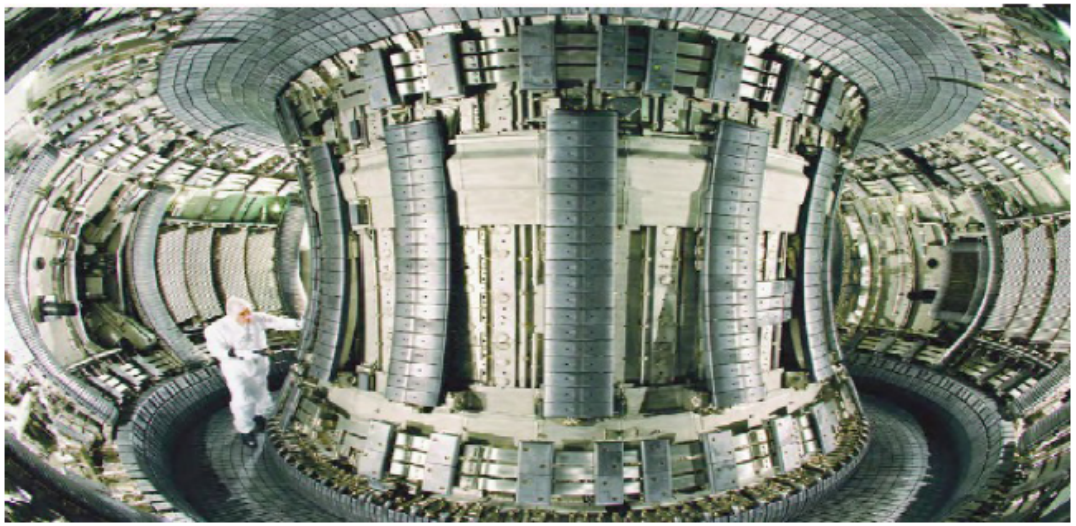
Plasma Applications: Universe



Plasma Applications: ICF



Plasma Applications: MCF



Joint European Torus (JET) is currently World's Largest Tokamak 16 MW

ITER

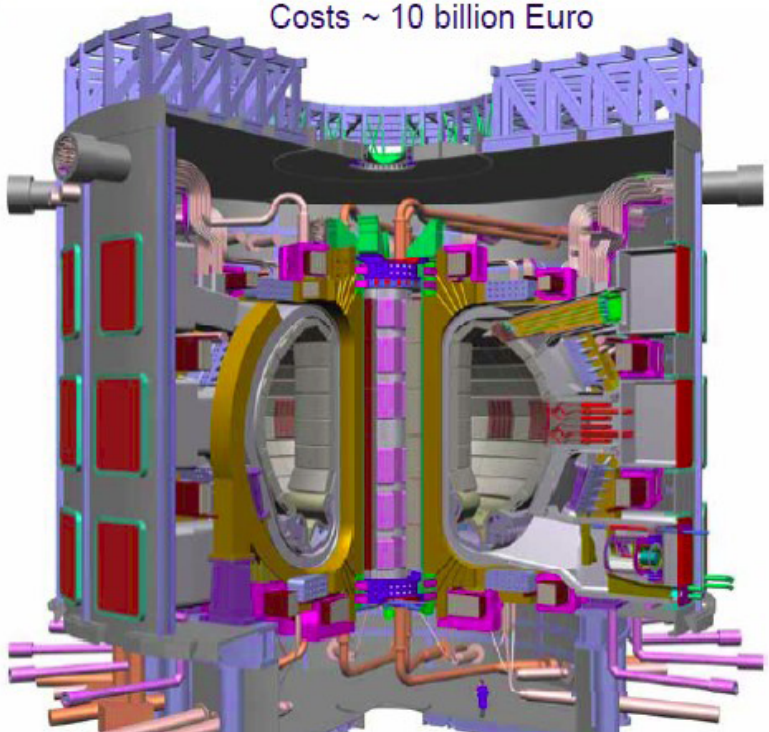
European Union
Japan
China
India
Korea
Russia
USA

Cadarache, France

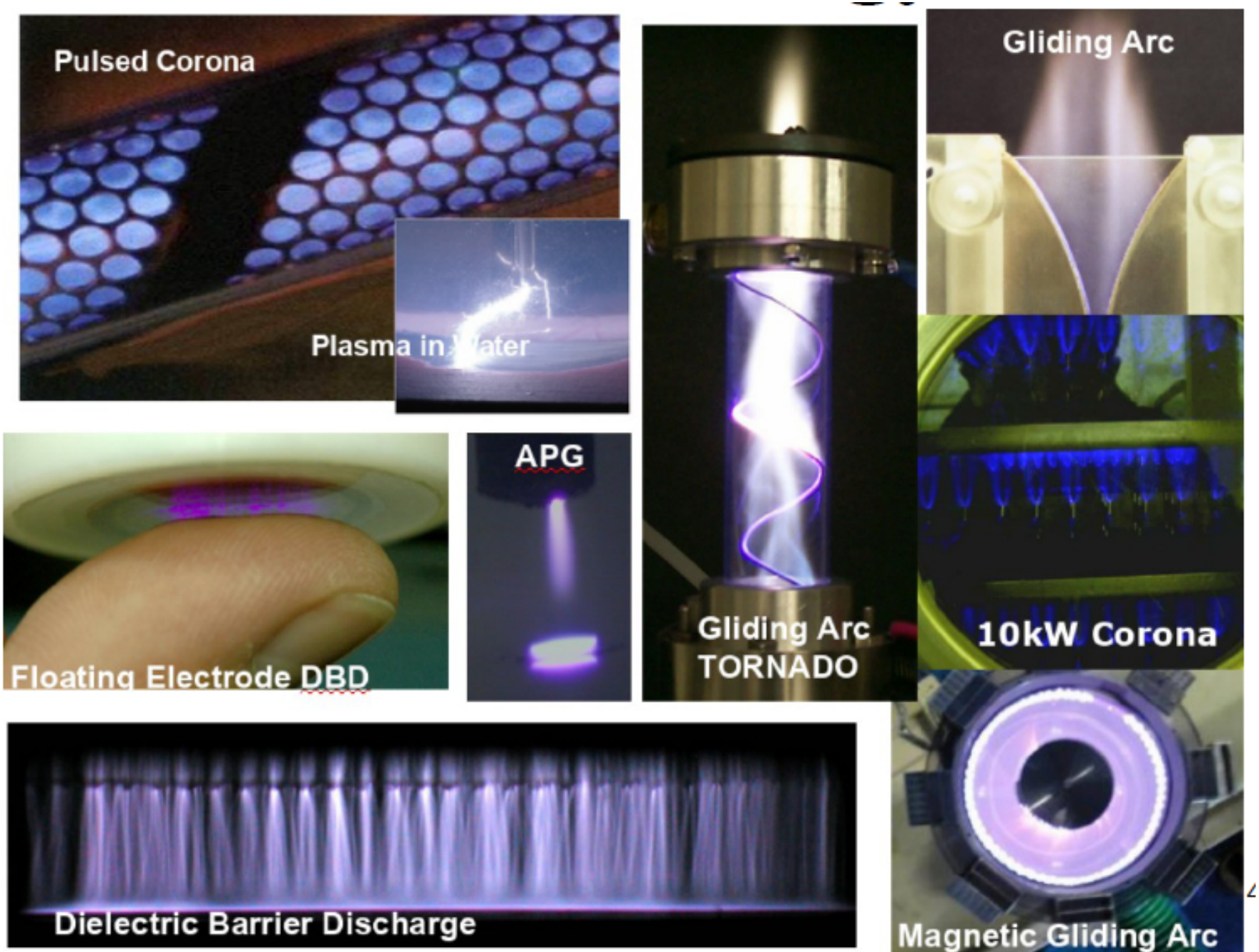
Goals:

- Q=10
- α-physics
- Tritium-cycle
- Neutrons
- cont. operation
- Material science

Costs ~ 10 billion Euro



Plasma Applications: Technology



Plasma Applications: Biology

Wound Healing: Suppurated Burns

Plasma Technologies, Inc

Wound Healing: Trophic Venous Ulcers

Broad Necrotic Suppurated Ulcer (Diabetic Peripheral Neuropathy)

Further reading

- Francis F. Chen: Introduction to Plasma Physics and Controlled Fusion, 3rd edn (Springer International Publishing Switzerland, 2016).

- Umran Inan, Marek Gołkowski: *Principles of Plasma Physics for Engineers and Scientists*, (Cambridge University Press, 2011).

- Dwight R Nicholson, *Introduction To Plasma Theory*, (Wiley, 1983).

- J. A. Bittencourt, *Fundamentals of Plasma Physics*, 3rd edn (New York: Springer-Verlag, 2004).

- N. A. Krall and A. W. Trivelpiece, *Principles of Plasma Physics*, (San Francisco: San Francisco Press, 1986).

Thanks for your attention!