PHYS4150 — PLASMA PHYSICS

LECTURE 1 - WHAT IS A PLASMA

Sascha Kempf[*]

G135, University of Colorado, Boulder

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What is a plasma? What is plasma physics?

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1 PLASMAS

1.1 *History*

- The word plasma comes from ancient greek ($\pi\lambda\alpha\sigma\mu\alpha$) meaning jelly substance.
- **1839:** Czech physiologist *Jan Purkinje* termed the liquid substance in cells "protoplasm".
- **1922:** *Irvine Langmuir* introduced the word "plasma" for the aggregate state because of its analogy to blood cells:

  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.[2]

1.2 *What is a plasma?*

Definition from our textbook:

A plasma is a quasineutral gas of charged and neutral particles which exhibits collective behavior[1].

Note the words "quasineutral" and "collective"!

[*] sascha.kempf@colorado.edu

1.3 *Examples for plasmas*

EVERYDAY LIFE On Earth plasmas are rather rare phenomena

- fluorescent lights
- neon signs
- street lights

INDUSTRIAL PLASMAS

- plasma displays
- arc furnaces

NATURAL PLASMAS

- Sun
- Solar wind
- ionosphere
- aurorae
- Van Allen belt
- lightning

RESEARCH PLASMAS

- fusion energy devices
- electron and ion beams
- laser produced plasmas
- plasma accelerators

1.4 *Example: Discharge Tubes*

Discharge phenomena are common in physics. A well known application is the Geiger-Müller detector used for measuring ionizing radiation. The underlying fundamental phenomenon is the *Townsend* discharge.

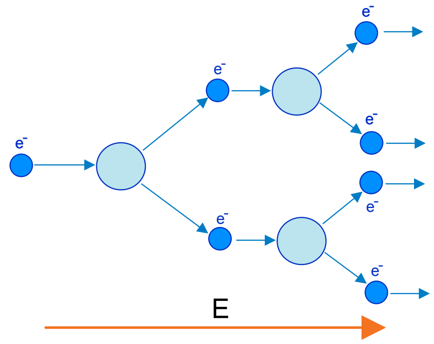


Figure 1: Townsend avalanche within an applied electric field

1.4.1 Townsend discharge

This is an avalanche process, where in a dilute gas electrons accelerated by an electric field collide with neutral molecules and subsequently create new free electrons, which in turn create more free electrons. The result is an avalanche multiplication of free electrons leading to an electric current through the gas. Based on experimental data John Townsend found that this current is well described by

$$I \sim e^{\alpha_n d},$$

where the *Townsend parameter* α_n is the number of free electrons generated per unit length and d is the tube length. To start the discharge avalanche process the applied voltage has to exceed the so-called *breakdown voltage* V_b of the tube.

1.4.2 Paschen's law

We now want to get a qualitative understanding about the dependence of the breakdown voltage V_b on the gas number density n and the tube length d. Lets us consider the extreme cases:

1. d fixed

   LOW n: electron free path length $\lambda > d \to$ high V_b

   HIGH n: too many collisions $\to$ high V_b

2. n fixed

   SHORT d: electron free path length $\lambda > d \to$ high V_b

   LARGE d: too many collisions $\to$ high V_b

From this follows that $V_b \sim n \cdot d$ is minimum for a combination of intermediate values of d and n. The relation between the breakdown voltage and $n \cdot d$ is known as *Schematic Paschen curve*.

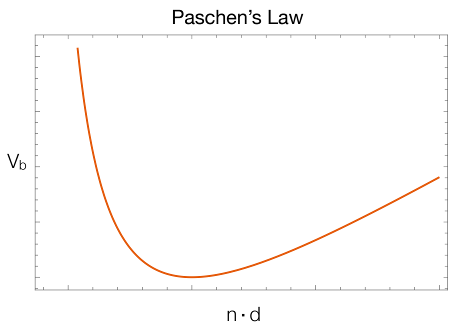


Figure 2: Paschen's law

2 WHAT ARE THE RELEVANT EQUATIONS?

MECHANICS Classical mechanics tells us how the particles respond to a applied force, which in our case is the Lorentz force:

$$\mathbf{F} = m \cdot \mathbf{a} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

ELECTRODYNAMICS Electrodynamics tells us how electric charges generate electric fields and electric currents generate magnetic fields:

$$\mathbf{j} = n \cdot q \cdot \mathbf{v}$$

Gauss's law

$$\nabla \cdot \mathbf{E} = \frac{1}{\epsilon_0}\rho = \frac{1}{\epsilon_0} n \cdot q$$

Gauss's law for magnetism

$$\nabla \cdot \mathbf{B} = 0$$

Faraday's law

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Ampere's law

$$\nabla \times \mathbf{B} = \mu \mathbf{j} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}$$

STATISTICAL MECHANICS Statistical mechanics tells us how the velocity distribution of the plasma particles relates to the temperature of the gas:

Boltzman distribution, we will talk about it in the next lecture

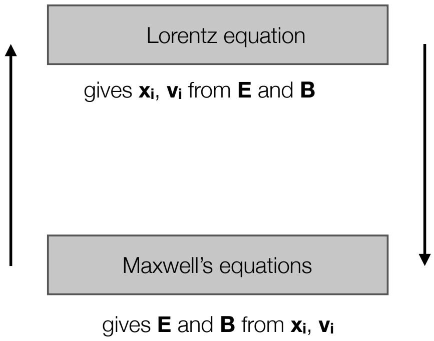
$$f(v) \sim e^{-\frac{mv^2}{2kT}} \text{ for ions and electrons}$$

The equations are interconnected with each other:

3 WHY ARE PLASMAS INTERESTING?

Plasma behaves collectively:

- Equations for **E**, **B**, **j** must be solved simultaneously



  - plasma charges affect **E**
  - plasma charges affect **B**

- each particle acts on all others

Challenge: We have to find appropriate approximations for the 10^{23} coupled equations.

References

[1] Francis F. Chen. *Introduction to Plasma Physics and Controlled Fusion*. 2016.

[2] I. Langmuir. Oscillations in Ionized Gases. *Proceedings of the National Academy of Science*, 14:627–637, August 1928.

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