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**TITLE**

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# Chapter 1

## Introduction

In this thesis ...

# Chapter 2

## Electromagnetism and Laser Profiles

### 2.1 Classical Electrodynamics

The main principles and laws that govern the phenomena behind lasers, plasma and their interaction are those of classical electrodynamics. As such, like many others tackling this area of research, I find that adding an overview of electrodynamics is simply mandatory. My aim when it comes to differentiating this introductory review from the millions of others out there, if at all possible, is to offer thorough calculations and explanations on some aspects where I personally felt like I wanted to see things from a clearer perspective.

#### 2.1.1 Maxwell's Equations

The Maxwell equations are (Jackson 1999):

$$\nabla \cdot \mathbf{D} = \rho \quad (2.1a)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2.1b)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.1c)$$

$$\nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t}. \quad (2.1d)$$

In the absence of magnetic and polarizable media,  $\mathbf{D} = \varepsilon_0 \mathbf{E}$  and  $\mathbf{B} = \mu_0 \mathbf{H}$  and the equations become:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \quad (2.2a)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2.2b)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.2c)$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}, \quad (2.2d)$$

While most readers probably have already had at least a basic introduction to the phenomena from which these equations arise and are well acquainted to how to make use of these equations, I would direct those who haven't towards the book by Fleisch 2008

By extracting the current density from equation (2.2d), computing its divergence and then replacing the electric field term using equation (2.2a) one obtains the continuity equation, which relates only the field sources to one another:

$$\nabla \cdot \mathbf{j}(\mathbf{r}, t) + \frac{\partial \rho(\mathbf{r}, t)}{\partial t} = 0. \quad (2.3)$$

These equations are also complemented by the Lorentz force, which describes how the fields act on the sources. The expression of the Lorentz force in the continuous case is:

$$\mathbf{F} = \int_V d\mathbf{r}' \left[ \rho(\mathbf{r}', t) \mathbf{E}(\mathbf{r}', t) + \frac{1}{c} \mathbf{j}(\mathbf{r}', t) \times \mathbf{B}(\mathbf{r}', t) \right].$$

### 2.1.2 The Scalar and Vector Potentials

Since the electric ( $\mathbf{E}$ ) and magnetic ( $\mathbf{B}$ ) fields are vectors, they can be described together by a total of six quantities. The sources on the other hand can be described using only four quantities: the electric charge density  $\rho$  and the three components of the electric current density  $\mathbf{j}$ . This points to the fact that there is a more convenient way to describe the fields. In finding this alternative, we shall employ the following basic results from algebra:

$$\nabla \cdot (\nabla \times \mathbf{v}) = 0 \quad (2.4a)$$

$$\nabla \times (\nabla \cdot \mathbf{v}) = 0 \quad (2.4b)$$

$$\nabla \times (\nabla f) = 0, \quad (2.4c)$$

which are valid for any vector function  $\mathbf{v}$  and for any scalar function  $f$ .

From equations (2.2b) and (2.4a) one can define the vector potential  $\mathbf{A}$  such that

$$\mathbf{B}(\mathbf{r}, t) = \nabla \times \mathbf{A}(\mathbf{r}, t). \quad (2.5)$$

By substituting (2.5) in (2.2c) one obtains

$$\nabla \times \left( \mathbf{E} + \frac{\partial \mathbf{A}}{\partial t} \right) = 0 \quad (2.6)$$

which together with equation (2.4c) defines the scalar potential  $\phi$

$$\nabla \phi(\mathbf{r}, t) = -\mathbf{E}(\mathbf{r}, t) - \frac{\partial \mathbf{A}}{\partial t}. \quad (2.7)$$

Using this in equation (2.2a)

$$\nabla^2 \phi + \frac{\partial}{\partial t} \nabla \cdot \mathbf{A} = -\frac{\rho}{\epsilon_0}. \quad (2.8)$$

Similarly, using equation (2.7) in equation (2.2d) and making use of the following vector identity

$$\nabla \times (\nabla \times \mathbf{v}) = \nabla(\nabla \cdot \mathbf{v}) - \nabla^2 \mathbf{v}, \quad (2.9)$$

another equation of the potentials is obtained

$$\nabla^2 \mathbf{A} - \frac{1}{c^2} \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu_0 \mathbf{j} + \nabla \left( \nabla \cdot \mathbf{A} + \frac{1}{c^2} \frac{\partial \phi}{\partial t} \right). \quad (2.10)$$

Considering that at every step in the derivation of equations (2.8) and (2.10) we only imposed the Maxwell equations and basic algebraic identities, it follows that equations (2.8)

and (2.10) and equation (2.2) are completely equivalent. We now have reduced the six quantities describing the fields to only four: the scalar potential  $\phi$  and the three components of the vector potential  $\mathbf{A}$ . This description of the fields through the potentials is quite useful since it is easily integrated in the formalism of special relativity. One can define the electromagnetic potential 4-vector such that the scalar field is the time-like component and the vector field is the space-like component.

In general, when studying the dynamics of particles in an electromagnetic field, once the potentials are computed using equations (2.8) and (2.10) the fields are obtained from equations (2.5) and (2.7) and can be used further in the expression of the Lorentz force.

### 2.1.3 Gauge Transformation

By a direct application of equation (2.4) one can show that a simultaneous transformation by an arbitrary well-behaved (continuous with continuous derivatives) scalar function  $f = f(\mathbf{r}, t)$  of the potentials:

$$\phi \rightarrow \phi + \frac{\partial f}{\partial t} \quad (2.11a)$$

$$\mathbf{A} \rightarrow \mathbf{A} - \nabla f, \quad (2.11b)$$

leaves the electric and magnetic field unchanged. This is actually a quite natural equivalent of the intuitive fact that any potential is defined up to a constant. In the particular case of the electromagnetic potential, equation (2.11) define a gauge transformation. There are two widely used gauges.

#### Lorenz gauge

$$\nabla \cdot \mathbf{A} + \frac{1}{c^2} \frac{\partial \phi}{\partial t} = 0 \quad (2.12)$$

This gauge cancels the gradient in equation (2.10). If one works in the usual Minkowski metric (Weinberg 1972)

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2.13)$$

the d'Alembert operator is then defined as

$$\square = \partial^\mu \partial_\mu = \eta^{\mu\nu} \partial_\nu \partial_\mu = \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2},$$

where  $\mu, \nu = \overline{0, 3}$  with 0 being the temporal index and 1, 2, 3 being the spatial indices (note: in this thesis I use Einstein's summation convention whenever there is an index repeated once up and down, *i.e.* it appears as both variant and covariant in a product). By replacing this definition in equations (2.8) and (2.10), it is easy to see that both  $\mathbf{A}$  and  $\phi$  obey a free wave equation:

$$\square \mathbf{A} = -\mu_0 \mathbf{j} \quad (2.14a)$$

$$\square \phi = -\frac{\rho}{\varepsilon_0}. \quad (2.14b)$$



**Coulomb Gauge** (sometimes found as transversal/velocity gauge)

$$\nabla \cdot \mathbf{A} = 0 \quad (2.15)$$

Under this gauge, the potential equations (2.8) and (2.10) take the form:

$$\square \mathbf{A} = -\mu_0 \mathbf{j} + \frac{1}{c^2} \nabla \frac{\partial \phi}{\partial t} \quad (2.16a)$$

$$\nabla^2 \phi = -\frac{\rho}{\varepsilon_0}. \quad (2.16b)$$

### Getting Back the Fields

In principle, one can choose the most convenient gauge for his system, solve the corresponding potential equations, then recover the electric and magnetic fields with

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla \phi \quad (2.17a)$$

$$\mathbf{B} = \nabla \times \mathbf{A}. \quad (2.17b)$$

### 2.1.4 The Poynting Theorem

The Poynting theorem is the form of the conservation of energy in the case of electromagnetic fields interacting with charges and currents. Since it is such an important and general result, this presentation of it will start from the more general form of the Maxwell equations equation (2.1).

In the derivation of this theorem, one usually starts from the local form of the Lorentz force (Griffiths 1999):

$$\mathbf{F} = \delta q \mathbf{E} + \delta q \mathbf{v} \times \mathbf{B}$$

The work done by the electric field part of the force on the volume element with charge  $\delta q$  and velocity  $\mathbf{v} = \frac{d\mathbf{l}}{dt}$  is

$$dW_e = q d\mathbf{l} \cdot \mathbf{E}$$

and the corresponding rate of work done is

$$\frac{dW_e}{dt} = q \mathbf{v} \cdot \mathbf{E}$$

while for the magnetic part we have (as expected)

$$dW_m = d\mathbf{l} \cdot \mathbf{F}_b = q d\mathbf{l} \cdot (\mathbf{v} \times \mathbf{B})$$

$$\frac{dW_b}{dt} = q \mathbf{v} \cdot (\mathbf{v} \times \mathbf{B}) = 0.$$

Adding these contributions and generalizing for the case of a distribution of charges and currents one obtains

$$\frac{dW}{dt} = \int_V d\mathbf{r} \mathbf{E} \cdot \mathbf{j} \quad (2.18)$$

By extracting  $\mathbf{j}$  from equation (2.1d) and replacing in the above equation we have

$$\frac{dW}{dt} = \int_V d\mathbf{r} \left[ \mathbf{E} \cdot (\nabla \times \mathbf{H}) - \mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t} \right]$$

Employing here the vector identity here

$$\nabla(\mathbf{u} \times \mathbf{v}) = \mathbf{v} \cdot (\nabla \times \mathbf{u}) - \mathbf{u} \cdot (\nabla \times \mathbf{v}) \quad (2.19)$$

gives

$$\frac{dW}{dt} = \int_V d\mathbf{r} \left[ \mathbf{H} \cdot (\nabla \times \mathbf{E}) - \nabla(\mathbf{E} \times \mathbf{H}) - \mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t} \right].$$

Replacing the curl of  $\mathbf{E}$  using Faraday's law (2.1c) we finally obtain

$$\frac{dW}{dt} = - \int_V d\mathbf{r} \left[ \nabla(\mathbf{E} \times \mathbf{H}) + \mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t} + \mathbf{H} \cdot \frac{\partial \mathbf{B}}{\partial t} \right].$$

If we restrict the discussion now only to linear media (*i.e.*  $\mathbf{D} = \varepsilon \mathbf{E}$  and  $\mathbf{B} = \mu \mathbf{H}$ ) a new important quantity can be defined

$$w_{em} = \frac{1}{2}(\mathbf{E} \cdot \mathbf{D} + \mathbf{H} \cdot \mathbf{B}) \quad (2.20)$$

which leads to a new way to write the expression of the rate of work done by the electromagnetic field

$$\frac{dW}{dt} = - \int_V d\mathbf{r} \left[ \nabla(\mathbf{E} \times \mathbf{H}) + \frac{\partial w_{em}}{\partial t} \right], \quad (2.21)$$

where the Poynting vector is

$$\mathbf{S} = \mathbf{E} \times \mathbf{H}. \quad (2.22)$$

In order to complete the derivation of Poynting's theorem, we must see how it is to be interpreted. As such, a short parenthesis concerning  $w_{em}$  is in order.

### Electrostatic field energy density

For a system of  $N$  stationary point-like charged particles of charges  $q_i$  placed at  $\mathbf{r}_i$ ,  $i = \overline{1, N}$  in a medium with permittivity  $\varepsilon$ , the total potential energy of the system, when neglecting the infinite self-interaction terms, is (Jackson 1999)

$$W_e = \frac{1}{2} \sum_{i,j=1, i \neq j}^N \frac{q_i q_j}{4\pi\varepsilon |\mathbf{r}_i - \mathbf{r}_j|}$$

or, factoring out the scalar potential  $\phi(\mathbf{r}_i)$  generated by all the other particles at the position of particle  $i$ ,

$$W_e = \frac{1}{2} \sum_{i=1}^N q_i \phi(\mathbf{r}_i)$$

This is easily generalized in integral form

$$W_e = \frac{1}{2} \int_V d\mathbf{r} \rho(\mathbf{r}) \phi(\mathbf{r}),$$

where we use the delta-Dirac function for pointlike particles if needed.

Using the fact that the electrostatic potential is defined by  $\mathbf{E} = -\nabla\phi$  and replacing this in equation (2.1a) one obtains the poison equation

$$\nabla^2\phi = -\frac{\rho}{\varepsilon}. \quad (2.23)$$

With this, the integral above becomes

$$W_e = \frac{\varepsilon}{2} \int_V d\mathbf{r} \phi \nabla^2\phi = -\frac{\varepsilon}{2} \int_V d\mathbf{r} \phi \nabla\phi + \frac{\varepsilon}{2} \int_V d\mathbf{r} |\nabla\phi|^2,$$

where integration by parts has been used.

In order to reach the desired result, we still have to perform one more integration by parts

$$\int_V d\mathbf{r} \phi \nabla\phi = \frac{1}{2} \int_V d\mathbf{r} \nabla\phi^2 = \int_{S_V} d\mathbf{a} \phi^2,$$

where in the last step we used Gauss' theorem. Now, if we integrate over the entire space and keep in mind that the electrostatic potential should be zero at infinity, the above integral becomes null. Using again the relation between the gradient of the potential and the electric field we get

$$W_e = \frac{\varepsilon}{2} \int_V d\mathbf{r} \mathbf{E}^2 \quad (2.24)$$

or, equivalently,

$$W_e = \frac{1}{2} \int_V d\mathbf{r} \mathbf{E} \cdot \mathbf{D}. \quad (2.25)$$

This leads to the definition of the energy density of the electrostatic field

$$w_e = \frac{1}{2} \mathbf{E} \cdot \mathbf{D}. \quad (2.26)$$

## Magnetostatic field energy density

This time around we start with a current loop in the case of magnetostatics ( $\nabla \cdot \mathbf{j} = 0$ ). No matter the current distribution in space, since the current density is rotational, we can always divide it in individual infinitesimal current loops. A change in the magnetic flux through such a loop is given by the integral form of Faraday's law (2.1c)

$$e = \oint_{\gamma} d\mathbf{l} \cdot \mathbf{E} = -\frac{d\phi_B}{dt}, \quad (2.27)$$

where  $\gamma$  is the closed curve describing the loop and  $\phi_B$  is the magnetic flux through the loop.

Since the autoinduced magnetic flux is  $\phi_B = LI$ , where  $L$  is the inductance of the loop and  $I$  the intensity of the electric current flowing in it, the electromotive force caused by autoinduction is

$$e = -L \frac{dI}{dt}.$$

Thus the rate of work against the increase of the current is

$$\frac{dW_B}{dt} = -Ie = LI \frac{dI}{dt} = \frac{d}{dt} \left( \frac{LI^2}{2} \right).$$

With this result we obtain the energy necessary to get a current of intensity  $I$  starting through a loop:

$$W_B = \frac{LI^2}{2}.$$

We will now eliminate  $L$  the same way we introduced it

$$\phi_B = LI = \int_{S_\gamma} d\mathbf{a} \cdot \mathbf{B} = \int_{S_\gamma} d\mathbf{a} \cdot (\nabla \times \mathbf{A}) = \oint_\gamma d\mathbf{l} \cdot \mathbf{A},$$

where the vector potential was introduced and Stokes' theorem was applied.

$$W_B = \frac{1}{2} I \oint_\gamma d\mathbf{l} \cdot \mathbf{A} = \frac{1}{2} \int_V d\mathbf{r} \mathbf{j} \cdot \mathbf{A}.$$

Here we naturally introduced the electric current density in our calculations. It can be replaced though using equation (2.1d) (we work in the confinements of magnetostatics, so there is no time dependent electric field)

$$W_B = \frac{1}{2} \int_V d\mathbf{r} \mathbf{A} \cdot (\nabla \times \mathbf{H}).$$

We employ here the identity (2.19) to reach

$$W_B = \frac{1}{2} \int_V d\mathbf{r} \mathbf{H} \cdot (\nabla \times \mathbf{A}) - \frac{1}{2} \int_V d\mathbf{r} \nabla \cdot (\mathbf{A} \times \mathbf{H}) = \frac{1}{2} \int_V d\mathbf{r} \mathbf{H} \cdot \mathbf{B} - \frac{1}{2} \int_{S_V} d\mathbf{a} \cdot (\mathbf{A} \times \mathbf{H}).$$

The same trick as in the previous subsection is applicable here. By extending the integration volume over the entire space and using the fact that the vector potential should be zero at infinity, the second integral vanishes.

$$W_B = \frac{1}{2} \int_V d\mathbf{r} \mathbf{H} \cdot \mathbf{B} \tag{2.28}$$

The energy density of the magnetostatic field is defined to be

$$w_B = \frac{1}{2} \mathbf{H} \cdot \mathbf{B}. \tag{2.29}$$

### Interpretation of the Poynting theorem

We can see now that (2.20) is simply the sum of equation (2.26) and equation (2.29). Summing up all the previous considerations,  $w_{em}$  holds the meaning of the energy density of the electromagnetic field itself, that is, the energy density present in space due to the presence of the electric and magnetic fields.

The Poynting theorem (2.21) can be rewritten using Gauss' theorem in its integral form

$$\frac{dW}{dt} = - \int_{S_V} d\mathbf{a} \cdot \mathbf{S} - \frac{d}{dt} \int_V d\mathbf{r} w_{em} \tag{2.30}$$

or in its differential form by eliminating the integrals

$$\mathbf{E} \cdot \mathbf{j} = -\nabla \cdot \mathbf{S} - \frac{\partial w_{em}}{\partial t}. \quad (2.31)$$

The Poynting vector has units of  $\frac{J}{m^2s}$  and describes the flux of energy through a surface. From this, we can conclude that the physical meaning behind equations (2.30) and (2.31) is that the rate of change in time of the energy inside a volume added with the flow of energy in and out of that volume is equal to minus the work done by the fields on the sources inside the volume.

### 2.1.5 Momentum of a System of Fields and Field Sources

By taking the vector product of  $\mathbf{D}$  with equation (2.1c) and of  $\mathbf{B}$  with equation (2.1d) and then adding them up the following equality can be obtained:

$$\mathbf{D} \times (\nabla \times \mathbf{E}) + \mathbf{B} \times (\nabla \times \mathbf{H}) = -\mathbf{j} \times \mathbf{B} - \frac{\partial}{\partial t}(\mathbf{D} \times \mathbf{B}). \quad (2.32)$$

We will restrict this discussion to the case where there is no polarizable or magnetic media:

$$\varepsilon_0 \mathbf{E} \times (\nabla \times \mathbf{E}) + \frac{1}{\mu_0} \mathbf{B} \times (\nabla \times \mathbf{B}) = -\mathbf{j} \times \mathbf{B} - \varepsilon_0 \frac{\partial}{\partial t}(\mathbf{E} \times \mathbf{B}). \quad (2.33)$$

Considering that the speed of light in vacuum is  $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$ , equation (2.34) becomes

$$\varepsilon_0 (\mathbf{E} \times (\nabla \times \mathbf{E}) + c^2 \mathbf{B} \times (\nabla \times \mathbf{B})) = -\mathbf{j} \times \mathbf{B} - \varepsilon_0 \frac{\partial}{\partial t}(\mathbf{E} \times \mathbf{B}). \quad (2.34)$$

In order to proceed, some vector algebra must be discussed. In particular, we would like to evaluate the following expression:

$$\mathbf{v}(\nabla \cdot \mathbf{v}) - \mathbf{v} \times (\nabla \times \mathbf{v})$$

We have

$$\begin{aligned} \mathbf{v} \times (\nabla \times \mathbf{v}) &= \mathbf{e}^i \varepsilon_{ijk} v^j (\nabla \times \mathbf{v})_k = \mathbf{e}^i \varepsilon_{ijk} v^j \varepsilon^{lmk} \partial_l v_m = \\ &= \mathbf{e}^i (\delta_i^l \delta_j^m - \delta_i^m \delta_j^l) v^j \partial_l v_m = \mathbf{e}^i [v^j \partial_i v_j - v^j \partial_j v_i] \end{aligned}$$

and

$$\mathbf{v}(\nabla \cdot \mathbf{v}) = \mathbf{e}^i v_i \partial_j v^j,$$

where  $\varepsilon_{ijk}$  is the Levi-Civita tensor,  $\delta_i^j$  is the Kronecker-delta symbol and  $\mathbf{e}^i$ ,  $i = \overline{1,3}$  are the Cartesian versors. Subtracting these two expressions leads to

$$\mathbf{v}(\nabla \cdot \mathbf{v}) - \mathbf{v} \times (\nabla \times \mathbf{v}) = \mathbf{e}^i [v_i \partial_j v^j - v^j \partial_i v_j + v^j \partial_j v_i] = \mathbf{e}^i [\partial_j (v_i v^j) - v^j \partial_i v_j].$$

Since

$$\partial_i (v^j v_j) = 2v^j \partial_i v_j,$$

we have

$$\mathbf{v}(\nabla \cdot \mathbf{v}) - \mathbf{v} \times (\nabla \times \mathbf{v}) = \mathbf{e}^i \left[ \partial_j (v_i v^j) - \frac{1}{2} \partial_i (v_j v^j) \right],$$

The second term can be stylized by introducing a Kronecker-delta and writing  $v_j v^j$  as  $\mathbf{v}^2$ , which leads to the desired final result

$$\mathbf{v}(\nabla \cdot \mathbf{v}) - \mathbf{v} \times (\nabla \times \mathbf{v}) = \mathbf{e}^i \partial_j \left[ v_i v^j - \frac{1}{2} \mathbf{v}^2 \delta_i^j \right] = \mathbf{e}_i \partial_j \left[ v^i v^j - \frac{1}{2} \mathbf{v}^2 \delta^{ij} \right]. \quad (2.35)$$

The last step is possible due to the fact that we only work with space-like components and we chose the convenient metric (2.13).

By defining the Maxwell stress tensor as

$$T^{ij} = \varepsilon_0 \left[ E^i E^j + c^2 B^i B^j - \frac{1}{2} (\mathbf{E}^2 + c^2 \mathbf{B}^2) \delta^{ij} \right] \quad (2.36)$$

and using it along with equation (2.35) in equation (2.34) one gets

$$\mathbf{e}_i \partial_j T^{ij} = \varepsilon_0 \mathbf{E}(\nabla \cdot \mathbf{E}) + \frac{1}{\mu_0} \mathbf{B}(\nabla \cdot \mathbf{B}) + \mathbf{j} \times \mathbf{B} + \varepsilon_0 \frac{\partial}{\partial t} (\mathbf{E} \times \mathbf{B})$$

Using Maxwell's equations (2.2a) and (2.2b) together with the definition of the Poynting vector (2.22) the above expression is simplified to the law of momentum conservation

$$\mathbf{e}_i \partial_j T^{ij} = \rho \mathbf{E} + \mathbf{j} \times \mathbf{B} + \frac{1}{c^2} \frac{\partial \mathbf{S}}{\partial t} \quad (2.37)$$

or

$$\mathbf{e}_i \partial_j T^{ij} = \rho \mathbf{E} + \mathbf{j} \times \mathbf{B} + \frac{\partial \mathbf{g}}{\partial t}, \quad (2.38)$$

where the volumic density of the fields' electromagnetic momentum  $\mathbf{g}$  is defined to be

$$\mathbf{g} = \frac{1}{c^2} \mathbf{S} = \mathbf{D} \times \mathbf{B}. \quad (2.39)$$

By observing that when integrating over a volume, the  $\rho \mathbf{E} + \mathbf{j} \times \mathbf{B}$  is simply the Lorentz force and that  $\mathbf{e}_i \partial_j T^{ij} = \nabla \cdot \hat{T}$  we reach an integral form of the momentum conservation

$$\frac{d}{dt} (\mathbf{P}_{\text{em}} + \mathbf{P}_{\text{mech}}) = \int_{\mathcal{V}} d\mathbf{r} \nabla \cdot \hat{T} = \int_{S_{\mathcal{V}}} d\mathbf{a} \cdot \hat{T}, \quad (2.40)$$

where  $\mathbf{P}_{\text{em}}$  and  $\mathbf{P}_{\text{mech}}$  are the electromagnetic and mechanical momenta, respectively. If we integrate over the entire space and use the fact that the stress tensor vanishes at infinity, we obtain

$$\frac{d}{dt} (\mathbf{P}_{\text{em}} + \mathbf{P}_{\text{mech}}) = 0. \quad (2.41)$$

## 2.2 Electromagnetic Waves

The short review of classical electrodynamics had as an ultimate goal to introduce the definitions, equations and formalism required in order to study electromagnetic waves. In this section I will start from the definition and properties of an electromagnetic wave and I will follow up with how one can describe laser pulses. The second part will contain a short introduction to the laser profiles used in research.

### 2.2.1 Maxwell's Equations in Vacuum

The concept of electromagnetic waves arises naturally from the Maxwell equations equation (2.1) if we consider them in the absence of any sources

$$\nabla \cdot \mathbf{D} = 0 \quad (2.42a)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2.42b)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.42c)$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} . \quad (2.42d)$$

The last equation (2.42d) can be rewritten using  $\mathbf{H} = \frac{1}{\mu} \mathbf{B}$  and  $\mathbf{D} = \varepsilon \mathbf{E}$  as

$$\nabla \times \mathbf{B} = \varepsilon \mu \frac{\partial \mathbf{E}}{\partial t} \quad (2.43)$$

By taking the curl of equation (2.42c) one gets

$$\nabla \times (\nabla \times \mathbf{E}) + \frac{\partial}{\partial t} (\nabla \times \mathbf{B}) = 0 ,$$

which, using the vector identity

$$\nabla \times (\nabla \times \mathbf{v}) = \nabla(\nabla \cdot \mathbf{v}) - \nabla^2 \mathbf{v} \quad (2.44)$$

and equation (2.42a), becomes

$$\left[ \nabla^2 - \varepsilon \mu \frac{\partial^2}{\partial t^2} \right] \mathbf{E} = 0 . \quad (2.45)$$

Through an analogous procedure, one obtains that the magnetic field  $\mathbf{B}$  satisfies the same equation. Using the D'Alembertian defined in section 2.1.3 we can conclude that both the electric and magnetic fields satisfy the Helmholtz equation

$$\square \mathbf{E} = 0 \quad (2.46a)$$

$$\square \mathbf{B} = 0 , \quad (2.46b)$$

with  $v^2 = \frac{1}{\varepsilon \mu}$  giving the speed of the wave (also called phase velocity) and  $c^2 = \frac{1}{\varepsilon_0 \mu_0}$  the speed of electromagnetic waves in vacuum.

The reader most probably has encountered waves in various contexts before, but I will add a reminder of the relevant parameters describing solutions of the Helmholtz equation just for the sake of completeness:

- if  $\mathbf{n}$  is the unit vector along the direction of propagation, the wave vector is defined as  $\mathbf{k} = \mathbf{n}k$ , where  $k = \frac{2\pi}{\lambda}$  is the wave number and  $\lambda$  is the wavelength;
- if  $T$  is the period in time of the wave, the frequency is defined as  $\nu = \frac{1}{T}$  and, equivalently, the angular frequency is defined as  $\omega = 2\pi\nu$ ;
- $v = \lambda\nu = \frac{\omega}{k} = \frac{1}{\sqrt{\varepsilon\mu}}$  is the phase velocity and  $v_g = \frac{\partial\omega}{\partial k}$  is the group velocity.

There is one more property we can derive before discussing the particular solutions of equation (2.46), namely the transverse character of electromagnetic waves in vacuum.

A very general form for a solution of equation (2.46) can be written as

$$\mathbf{E} = \mathbf{E}_0 f(\mathbf{k} \cdot \mathbf{r} - \omega t),$$

where  $\mathbf{E}_0$  is a constant vector. Using it in equation (2.42c) leads to the following development

$$0 = \nabla \cdot \mathbf{E} = \nabla \cdot [\mathbf{E}_0 f(\mathbf{k} \cdot \mathbf{r} - \omega t)] = \mathbf{E}_0 \nabla f(\mathbf{k} \cdot \mathbf{r} - \omega t) = \mathbf{k} \cdot \mathbf{E}_0 f'(\mathbf{k} \cdot \mathbf{r} - \omega t)$$

which concludes that

$$\mathbf{k} \cdot \mathbf{E} = 0. \quad (2.47)$$

Similarly, equation (2.42c) leads to

$$-\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E} = \nabla \times [\mathbf{E}_0 f(\mathbf{k} \cdot \mathbf{r} - \omega t)] = \mathbf{k} \times \mathbf{E}_0 f'(\mathbf{k} \cdot \mathbf{r} - \omega t),$$

where in the last step this identity was used

$$\nabla \times (a\mathbf{v}) = a(\nabla \times \mathbf{v}) + (\nabla a) \times \mathbf{v}. \quad (2.48)$$

This suggests that

$$\mathbf{B} \propto \mathbf{k} \times \mathbf{E}. \quad (2.49)$$

Looking at equations (2.47) and (2.49) it is easy to conclude that the electromagnetic waves are transverse and that at any moment, the magnetic and electric fields are perpendicular to one another.

Note: Electromagnetic waves can only be transversal in “free space” or homogeneous media (Heaviside 1971). Longitudinal modes can also be achieved in special conditions, like inside confined spaces and in plasmas (Jackson 1999; Griffiths 1999). However, there has been work done on the production of longitudinal waves in vacuum (Wang *et al.* 2008) as a consequence of theoretical work showing the possibility of having a small longitudinal component in electromagnetic waves in vacuum (Cicchitelli, Hora, and Postle 1990) using an improved paraxial approximation.

## 2.2.2 Plane Waves

The simplest solution to the Helmholtz equation (2.46) is the plane wave

$$\sin(\mathbf{k} \cdot \mathbf{r} - \omega t + \delta) \quad (2.50)$$

In the research literature it is common to employ a complex formulation (Vrejoiu 1987). Thus, the complex fields are defined as

$$\tilde{\mathbf{E}}(\mathbf{r}, t) = E_0 \mathbf{s} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \quad (2.51a)$$

$$\tilde{\mathbf{B}}(\mathbf{r}, t) = B_0 \mathbf{n} \times \mathbf{s} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)}, \quad (2.51b)$$

where  $E_0$  and  $B_0$  are the real amplitudes and  $\mathbf{s}$  is a complex vector of norm one

$$\mathbf{s} = \mathbf{s}_r + i\mathbf{s}_i, \quad |\mathbf{s}|^2 = \mathbf{s}^* \cdot \mathbf{s} = \mathbf{s}_r^2 + \mathbf{s}_i^2 = 1$$



With this setup, the real fields are to be obtained as

$$\mathbf{E}(\mathbf{r}, t) = \text{Re}\left\{\tilde{\mathbf{E}}(\mathbf{r}, t)\right\} = E_0 [\mathbf{s}_r \cos(\mathbf{k} \cdot \mathbf{r} - \omega t) - \mathbf{s}_i \sin(\mathbf{k} \cdot \mathbf{r} - \omega t)] \quad (2.52a)$$

$$\mathbf{B}(\mathbf{r}, t) = \text{Re}\left\{\tilde{\mathbf{B}}(\mathbf{r}, t)\right\} = B_0 \mathbf{n} \times [\mathbf{s}_r \cos(\mathbf{k} \cdot \mathbf{r} - \omega t) - \mathbf{s}_i \sin(\mathbf{k} \cdot \mathbf{r} - \omega t)] . \quad (2.52b)$$

In what follows we are interested in analyzing the plane wave solution from the perspective of energy in the formalism developed in sections 2.1.4 and 2.1.5.

From the discussion in the previous subsection it is easy to deduce the relation between the magnetic and electric fields of a wave (it is the same for both the real and complex fields)

$$\tilde{\mathbf{B}} = \frac{1}{c} \mathbf{n} \times \tilde{\mathbf{E}} . \quad (2.53)$$

With this, the energy density (2.20) of the fields is

$$w_{em} = \frac{1}{2} \varepsilon_0 \mathbf{E}^2 + \frac{1}{2\mu_0} \mathbf{B}^2 = \varepsilon_0 \mathbf{E}^2 , \quad (2.54)$$

which can be computed using equation (2.52a) to be

$$w_{em} = \varepsilon_0 E_0^2 [\mathbf{s}_r^2 \cos^2(\mathbf{k} \cdot \mathbf{r} - \omega t) + \mathbf{s}_i^2 \sin^2(\mathbf{k} \cdot \mathbf{r} - \omega t) - \mathbf{s}_r \cdot \mathbf{s}_i \sin(2\mathbf{k} \cdot \mathbf{r} - 2\omega t)] . \quad (2.55)$$

This quantity could vary quite wildly in time depending on the wave's frequency, so we would rather compute a quantity that can be easured experimentally, which is of course the time average of the energy density

$$\langle w_{em} \rangle = \frac{1}{T} \int_0^T dt w_{em} = \frac{\varepsilon_0 E_0^2}{T} \int_0^T dt [\mathbf{s}_r^2 \cos^2(\mathbf{k} \cdot \mathbf{r} - \omega t) + \mathbf{s}_i^2 \sin^2(\mathbf{k} \cdot \mathbf{r} - \omega t) - \mathbf{s}_r \cdot \mathbf{s}_i \sin(2\mathbf{k} \cdot \mathbf{r} - 2\omega t)] . \quad (2.56)$$

Since we know that the average of sine over one period is zero and the averages of both sine and cosine squared over one period are one half, we get

$$\langle w_{em} \rangle = \frac{\varepsilon_0 E_0^2}{2} . \quad (2.57)$$

But looking at definition (2.51a) we see that

$$\langle w_{em} \rangle = \frac{\varepsilon_0}{2} \tilde{\mathbf{E}}^* \cdot \tilde{\mathbf{E}} . \quad (2.58)$$

In a very similar way we have for the Poynting vector the following developement

$$\mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \cdot \mathbf{B} = \frac{1}{\mu_0 c} \mathbf{n} \mathbf{E}^2 \quad (2.59)$$

$$\langle \mathbf{S} \rangle = \sqrt{\frac{\varepsilon_0}{\mu_0}} \langle \mathbf{E}^2 \rangle \mathbf{n} = \frac{1}{2} \sqrt{\frac{\varepsilon_0}{\mu_0}} E_0^2 \mathbf{n} = c \langle w_{em} \rangle \mathbf{n} \quad (2.60)$$

$$\langle \mathbf{S} \rangle = \frac{1}{2\mu_0} \tilde{\mathbf{E}} \times \tilde{\mathbf{B}}^* . \quad (2.61)$$

And, obviously, the electromagnetic momentum (2.39) is

$$\langle g \rangle = \left\langle \frac{1}{c^2} \mathbf{S} \right\rangle = \frac{\langle w_{em} \rangle}{c^2} \mathbf{n} . \quad (2.62)$$

## Polarization of Plane Waves

For any arbitrary complex field we can find a decomposition of the real field in orthogonal components. In order to do that, we make the following notations concerning the complex vector of (2.51a)

$$\mathbf{s} \cdot \mathbf{s} = \alpha^2 e^{2i\theta} \text{ with } \alpha, \theta \in \mathbb{R}. \quad (2.63)$$

We can define  $\mathbf{u} = \mathbf{s} e^{-i\theta}$  such that  $\mathbf{u}_r \cdot \mathbf{u}_i = 0$ . In this way the orthogonal coordinates system can be chosen as

$$\mathbf{e}_x = \frac{\mathbf{u}_r}{|\mathbf{u}_r|}, \quad \mathbf{e}_y = \pm \frac{\mathbf{u}_i}{|\mathbf{u}_i|}, \quad \mathbf{e}_z = \mathbf{n}, \quad (2.64)$$

with the sign of  $\mathbf{e}_y$  being conveniently chosen in order to have a right-handed system (*i.e.*  $\mathbf{e}_x \times \mathbf{e}_y = \mathbf{e}_z$ ).

The real field (2.52a) is in this basis

$$\mathbf{E} = E_0 [u_r \mathbf{e}_x \cos(\mathbf{k} \cdot \mathbf{r} - \omega t + \theta) \mp u_i \mathbf{e}_y \sin(\mathbf{k} \cdot \mathbf{r} - \omega t + \theta)] . \quad (2.65)$$

For time-independent  $\mathbf{e}_x$ ,  $\mathbf{e}_y$  and  $\mathbf{e}_z$ , the following cases are to be distinguished:

- $u_r, u_i$  arbitrary and non-zero: elliptically polarized wave;
- $u_r = u_i \neq 0$ : circularly polarized wave;
- either  $u_r = 0$  or  $u_i = 0$ : linearly polarized wave.

### 2.2.3 Paraxial Approximation

This and the next section discuss the ways in which we can describe beams of electromagnetic waves (like, say, laser beams) and follows ideas from Goldsmith 1998.

The paraxial approximation aims to simplify the Helmholtz equation

$$\left[ \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right] \psi = 0. \quad (2.66)$$

We can treat this equation by the method of separation of variables  $\psi = \zeta(\mathbf{r})T(t)$  in order for it to become

$$\frac{1}{\zeta} \nabla^2 \zeta = \frac{1}{c^2} \frac{T''}{T} = -k^2, \quad (2.67)$$

where  $k$  is simply the wave number. It is clear that the solution of the time equation is a combination of sine and cosine functions, so the real problem consists in solving the spatial equation

$$\nabla^2 \zeta + k^2 \zeta = 0. \quad (2.68)$$

In the particular case of electromagnetic waves, this equation must hold for the complex vector  $\bar{\mathbf{E}}$ , so it must hold for each of its components. The Helmholtz equation for the electric field can be reduced by considering a solution of the form

$$\zeta(\mathbf{r}) = u(\mathbf{r}) e^{-ikz}, \quad (2.69)$$

where the z-axis was chosen as the propagation direction for the wave.

Inserting (2.69) in equation (2.68) we get

$$\begin{aligned}
0 &= \nabla^2 \zeta + k^2 \zeta = (\partial_x^2 u + \partial_y^2 u) e^{-ikz} + \partial_z^2 (u e^{-ikz}) + k^2 u e^{-ikz} = \\
&= (\partial_x^2 u + \partial_y^2 u) e^{-ikz} + (\partial_z^2 u) e^{-ikz} - 2ik(\partial_z u) e^{-ikz} - k^2 u e^{-ikz} + k^2 u e^{-ikz} = \\
&= e^{-ikz} \nabla^2 u - 2ik e^{-ikz} \partial_z u.
\end{aligned}$$

Multiplying with  $e^{ikz}$  leads to

$$\nabla^2 u - 2ik \partial_z u = 0. \quad (2.70)$$

The first paraxial approximation argument says that, due to diffraction, the variation of the amplitude  $u$  along the direction of propagation is very small compared to distances of the order of the wave's wavelength. This can be summarized by the mathematical condition

$$\lambda \frac{\Delta(\partial_z u)}{\Delta z} \ll \partial_z u, \quad (2.71)$$

which indicates that the double partial derivative with respect to  $z$  (the propagation axis) is negligible compared to the  $2ik \partial_z u$  term. The second argument says that in the laplacian, the double partial derivative with respect to the  $z$ -axis can be neglected, such that one obtains

$$\partial_x^2 u + \partial_y^2 u - 2ik \partial_z u = 0. \quad (2.72)$$

which is the paraxial wave equation.

## 2.2.4 Gaussian Beams

One can find solutions to equation (2.72) working in various coordinate systems, but the most convenient and useful for our purpose (and in practical applications in general) is to work in cylindrical coordinated. In this case, the equation becomes

$$\partial_r^2 u + \frac{1}{r} \partial_r u + \frac{1}{r} \partial_\varphi^2 u - 2ik \partial_z u = 0. \quad (2.73)$$

To simplify our calculations even more, we can remove the  $\varphi$  dependence of  $u$ , which is to imply axial symmetry for the wave. This gives

$$\partial_r^2 u + \frac{1}{r} \partial_r u - 2ik \partial_z u = 0. \quad (2.74)$$

The radial part of the equation suggests that we should have a dependence of a complex exponential of  $r^2$ . An educated guess would be a Gaussian distribution-like function of the form

$$u(r, z) = G(z) e^{-i \frac{kr^2}{2q(z)}}, \quad (2.75)$$

where the complex functions  $G(z)$  and  $q(z)$  are to be determined. Let us do just that by inserting (2.75) in equation (2.74):

$$\partial_r u = -\frac{ikr}{q(z)} G(z) e^{-i \frac{kr^2}{2q(z)}}$$

$$\begin{aligned}\partial_r^2 u &= -\frac{ik}{q(z)}G(z) \left[1 - \frac{ikr^2}{q(z)}\right] e^{-i\frac{kr^2}{2q(z)}} \\ \partial_z u &= \left[G'(z) + \frac{ikr^2}{2q^2(z)}G(z)q'(z)\right] e^{-i\frac{kr^2}{2q(z)}}.\end{aligned}$$

Replacing these results and ridding ourselves of the exponential leads to

$$-2ik \left(\frac{G}{q} + G'\right) + \frac{k^2 r^2 G}{q^2}(q' - 1) = 0, \quad (2.76)$$

which gives the following differential equations for  $G$  and  $q$ :

$$\frac{dq}{dz} = 1 \quad (2.77a)$$

$$\frac{dG}{dz} = -\frac{G}{q}. \quad (2.77b)$$

The solution of equation (2.77a) is trivial

$$q(z) = q(z_0) + z - z_0,$$

which can be simplified by choosing our origin at  $z_0$

$$q(z) = q(0) + z. \quad (2.78)$$

The quantity  $q$  (which is actually complex) is often called *Gaussian beam parameter*. Since it appears in (2.75) as  $\frac{1}{q}$ , it is convenient to express it in the form

$$\frac{1}{q} = \left(\frac{1}{q}\right)_r - i \left(\frac{1}{q}\right)_i. \quad (2.79)$$

If we now substitute this in the guessed solution (2.75) we obtain

$$u(r, z) = G(z) e^{-\frac{ikr^2}{2} \left[\left(\frac{1}{q}\right)_r - i \left(\frac{1}{q}\right)_i\right]} = G(z) e^{-\frac{kr^2}{2} \left(\frac{1}{q}\right)_i} e^{-\frac{ikr^2}{2} \left(\frac{1}{q}\right)_r}. \quad (2.80)$$

The real part of  $\frac{1}{q}$  has physical significance. In order to see this, imagine that at a point  $z$  on the propagation direction we draw a plane perpendicular to the  $z$ -axis. If  $R$  would be the radius of curvature of the wavefront at point  $z$  (with respect to the position of the source), we can define  $\phi(r) = k\delta x$  to be the difference in phase between the wavefront and the plane as a function of  $r$ . Since we work in the paraxial approximation, we can consider that  $r \ll R$ , such that, using as reference figure 2.1, we have

$$\alpha \approx \frac{r}{R} \quad (2.81a)$$

$$\delta x = -R(1 - \cos(\alpha)) \approx R \frac{\alpha^2}{2} \quad (2.81b)$$

$$\phi(r) \approx -\frac{kr^2}{2} \frac{1}{R}. \quad (2.81c)$$

We can conclude now that

$$\left(\frac{1}{q}\right)_r = \frac{1}{R}. \quad (2.82)$$



Figure 2.1: A drawing showing how to compute  $\phi(r)$

The imaginary part of  $\frac{1}{q}$  appears in the real exponential. This exponential should thus give the Gaussian distribution form of the wave, that is it should look like

$$e^{-\left(\frac{r}{r_0}\right)^2}, \quad (2.83)$$

where  $r_0$  is proportional to the standard deviation. In this case we can write

$$\left(\frac{1}{q}\right)_i = \frac{2}{kw^2(z)} = \frac{\lambda}{\pi w^2(z)}. \quad (2.84)$$

This defines the *beam radius*  $w(z)$  as the value of  $r$  at which the field falls to  $\frac{1}{e}$  of its value on the  $z$ -axis. Putting these results together, we reach a final formula for  $\frac{1}{q}$

$$\frac{1}{q} = \frac{1}{R(z)} - i \frac{\lambda}{\pi w^2(z)}. \quad (2.85)$$

It is conventional to take  $\lim_{z \rightarrow 0} R(z) \rightarrow \infty$ , such that  $\frac{1}{q(0)} = -i \frac{\lambda}{\pi w_0^2}$ , and  $w_0 = w(0)$  is usually interpreted as the *beam waist radius*. If we look back at the solution (2.78), we can rewrite  $q$  in this formalism as

$$q = z + i \frac{\pi w_0^2}{\lambda}. \quad (2.86)$$

Playing around with equations (2.85) and (2.86) we have the following development

$$\begin{aligned} \frac{1}{q} &= \frac{1}{R} - i \frac{\lambda}{\pi w^2} = \frac{1}{z + i \frac{\pi w_0}{\lambda}} = \frac{z - i \frac{\pi w_0}{\lambda}}{z^2 + \left(\frac{\pi w_0^2}{\lambda}\right)^2} \\ \frac{1}{R} &= \frac{z}{z^2 + \left(\frac{\pi w_0^2}{\lambda}\right)^2} \Rightarrow R = z + \frac{1}{z} \left(\frac{\pi w_0^2}{\lambda}\right)^2 \\ \frac{1}{w^2} &= \frac{\frac{\pi^2 w_0^2}{\lambda^2}}{z^2 + \left(\frac{\pi w_0^2}{\lambda}\right)^2} \Rightarrow w = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2}. \end{aligned}$$

For the sake of clarity, I write again the expressions obtained for the radius of curvature and the beam radius

$$R = z + \frac{1}{z} \left( \frac{\pi w_0^2}{\lambda} \right)^2 \quad (2.87)$$

$$w = w_0 \sqrt{1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2} . \quad (2.88)$$

Turning back now to equation (2.77b), using (2.86), we can rewrite it as

$$\frac{dG}{G} = - \frac{d \left( z + i \frac{\pi w_0^2}{\lambda} \right)}{z + i \frac{\pi w_0^2}{\lambda}} ,$$

which, after integration, becomes

$$\ln \frac{G(z)}{G(0)} = \ln \frac{z + i \frac{\pi w_0^2}{\lambda}}{i \frac{\pi w_0^2}{\lambda}}$$

or

$$\frac{G(z)}{G(0)} = \frac{1}{1 - i \frac{\lambda z}{\pi w_0^2}} = \frac{1 + i \frac{\lambda z}{\pi w_0^2}}{1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2} . \quad (2.89)$$

For convenience, this is usually expressed in terms of a phasor (commonly called Gouy phase) defined as

$$\tan(\phi_0) = \frac{\lambda z}{\pi w_0^2} . \quad (2.90)$$

Now the solution for  $G$  is stylized to be

$$\frac{G(z)}{G(0)} = \frac{w_0}{w} e^{i\phi_0} . \quad (2.91)$$

Putting together equations (2.75), (2.85) and (2.91) we finally find  $u$

$$u(r, z) = G(0) \frac{w_0}{w} \exp \left( -\frac{r^2}{w^2} - i \frac{\pi r^2}{\lambda R} + i\phi_0 \right) \quad (2.92)$$

and, consequently, the solution to the paraxial wave equation with axial symmetry

$$\zeta(r, z) = G(0) \frac{w_0}{w} \exp \left( -\frac{r^2}{w^2} - ikz - i \frac{\pi r^2}{\lambda R} + i\phi_0 \right) . \quad (2.93)$$

### 2.2.5 Gaussian Beam Packets

In the research literature, it is a custom to use a parameter called *confocal distance* or *Reyleigh range*

$$z_0 = \frac{\pi w_0^2}{\lambda} . \quad (2.94)$$

Including it, all the relevant auxiliary functions become

$$R(z) = z + \frac{z_0^2}{z} \quad (2.95a)$$

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2} \quad (2.95b)$$

$$\phi_0(z) = \arctan\left(\frac{z}{z_0}\right). \quad (2.95c)$$

We can immediately observe that  $w(z)$  at  $z = z_0$  is actually equal to  $\sqrt{2}w_0$ . From this we can deduce that the  $z_0$  indicates how far from the origin the beam is collimated. It is very simple to understand by looking at figure 2.2



Figure 2.2: Gaussian beam radius  $w$  as a function of  $z$

We can also differentiate three cases of interest for the curvature radius  $R(z)$ . At  $z \rightarrow 0$ , *i.e.* near the waist,  $R \rightarrow \infty$ , so the profile is that of a plane wave. At the Rayleigh range, the curvature ( $\frac{1}{R}$ ) is maximum and, consequently, the radius itself is minimum ( $2z_0$ ). Finally, at very large distances away from the waist, the radius is equal to  $z$ , so the profile is spherical.

The Gouy phase is an important parameter in theoretical considerations, especially when it comes to higher order Gaussian modes, but is hard to observe experimentally. Physically, it modifies the wavelength near the waist (Paschotta 2020). This results also in a change of the phase velocity. As a consequence, the phase velocity near the waist can exceed the velocity of light in the medium, just as it might inside a waveguide.

Now that we understood the shape and behaviour of the Gauss beam, we are almost ready to define the electric and magnetic fields. But before that we must talk about normalization. While a look at (2.93) might not suggest the need for any normalization, physical arguments request it. We would like to not have unexplained losses of power as a function of  $z$  (remember that we are basically just setting the dependence of the fields on position right now). As such, a normalization of  $\zeta(r, z)$  over the transversal surface is necessary. That is, we want the intensity as a function of  $z$  to be just a constant. While in literature is very common to impose norm 1, I find it more useful to norm it to  $\pi w_0^2$ , as suggested by Dondera 2020, such that the final result is adimensional and it is easier to introduce the amplitude of the field. We have

$$\pi w_0^2 = \iint dr d\varphi r |\zeta|^2 = 2\pi |G(0)|^2 \int dr \left| \frac{w_0}{w} \right|^2 r e^{-2\frac{r^2}{w^2}} =$$

$$\begin{aligned}
&= \frac{1}{2} \pi \left( \frac{w_0}{w} \right)^2 |G(0)|^2 w^2 \int d \left( 2 \frac{r^2}{w^2} \right) e^{-2 \frac{r^2}{w^2}} = \\
&= \frac{1}{2} \pi w_0^2 G^2(0)
\end{aligned}$$

which gives the normalization constant

$$G(0) = \sqrt{2}. \quad (2.96)$$

### The Electric Field

The  $x$  and  $y$  components of the electric field are now expressed using equation (2.93) as

$$E_x(r, z) = \alpha_x E_0 \sqrt{2} \frac{w_0}{w} \exp \left( -\frac{r^2}{w^2} - i k z - i \frac{k r^2}{2R} + i \phi_0 \right) \quad (2.97a)$$

$$E_y(r, z) = \alpha_y E_0 \sqrt{2} \frac{w_0}{w} \exp \left( -\frac{r^2}{w^2} - i k z - i \frac{k r^2}{2R} + i \phi_0 \right), \quad (2.97b)$$

where we choose  $\alpha_x = 1$ ,  $\alpha_y = 0$  for linear polarization, and  $\alpha_x = \frac{1}{\sqrt{2}}$ ,  $\alpha_y = \pm \frac{i}{\sqrt{2}}$  for right and left-handed circular polarization, respectively. In order to obtain the  $z$  component, we have to impose the condition  $\nabla \cdot \mathbf{E} = 0$  and to use the approximation  $\partial_z E_z \approx -i k E_z$  (which holds if the pulse is long enough or quasi-rectangular). The immediate result is

$$E_z(r, z) = -\frac{i}{k} (\partial_x E_x(r, z) + \partial_y E_y(r, z)), \quad (2.98)$$

or, explicitly

$$E_z(r, z) = \frac{2 \left( i - \frac{z}{z_0} \right)}{k w^2(z)} [x E_x(r, z) + y E_y(r, z)]. \quad (2.99)$$

### The Magnetic Field

In order to derive the magnetic, one can impose the relation (2.53)

$$\mathbf{B} = \frac{1}{c} \mathbf{n} \times \mathbf{E} = \frac{1}{c} \mathbf{e}_z \times \mathbf{E} = \frac{1}{c} E_x \mathbf{e}_z \times \mathbf{e}_x + \frac{1}{c} E_y \mathbf{e}_z \times \mathbf{e}_y = -\frac{1}{c} E_y \mathbf{e}_x + \frac{1}{c} E_x \mathbf{e}_y,$$

which indicates that

$$B_x(r, z) = -\frac{1}{c} E_y(r, z) \quad (2.100a)$$

$$B_y(r, z) = \frac{1}{c} E_x(r, z). \quad (2.100b)$$

The third component is found exactly in the same way as for the electric field, taking into account that  $\nabla \cdot \mathbf{B} = 0$  and using the same approximation  $\partial_z B_z \approx -i k B_z$  (the conditions for its validity are the same):

$$B_z(r, z) = -\frac{i}{k} (\partial_x B_x(r, z) + \partial_y B_y(r, z)) = -\frac{i}{c k} (\partial_y E_x(r, z) - \partial_x E_y(r, z)), \quad (2.101)$$



or rather

$$B_z(r, z) = \frac{2 \left( i - \frac{z}{z_0} \right)}{ckw^2(z)} [yE_x(r, z) - xE_y(r, z)]. \quad (2.102)$$

## The Temporal Profile

One observation must be made now. These expressions only describe the spatial part of the field. In order to give the exact field we must add the time-dependent part of the solution  $e^{i\omega t}$ . However, this is not all there is to it. Since we are interested in describing laser beams, we must take into consideration the fact that the pulse has a finite duration. One does this by adding a Gaussian envelope over time. The time-dependent part will now be

$$g(z, t) = \exp \left( i\omega t - \left( \frac{t - \frac{z - z_F}{c}}{\tau_0} \right)^2 \right), \quad (2.103)$$

where  $\tau_0$  is the duration of the pulse and  $z_F$  is the original position of the intensity peak.

In what follows, I aim to provide a short proof of the fact that even with this envelope, the final fields are still solutions of Helmholtz equation under the paraxial approximation.

Let  $f(r, z)$  be the solution for

$$\partial_r^2 f + \frac{1}{r} \partial_r f - 2ik \partial_z f = 0. \quad (2.104)$$

The solution for the complete Helmholtz equation

$$\partial_r^2 u + \frac{1}{r} \partial_r u + \partial_z^2 u - \frac{1}{c} \partial_t^2 u = 0 \quad (2.105)$$

is proposed to be  $u(r, z) = f(r, z)g(z, t)e^{-ikz}$  such that we have

$$\partial_r^2 (fg e^{-ikz}) + \frac{1}{r} \partial_r (fg e^{-ikz}) + \partial_z^2 (fg e^{-ikz}) - \frac{1}{c^2} \partial_t^2 (fg e^{-ikz}) = 0$$

$$(\partial_r^2 f + \frac{1}{r} \partial_r f) g e^{-ikz} + (\partial_z^2 f) g e^{-ikz} + 2(\partial_z f) \partial_z (g e^{-ikz}) + f \partial_z^2 (g e^{-ikz}) - \frac{1}{c^2} f \partial_t^2 (g e^{-ikz}) = 0.$$

The paraxial approximation allows us to ignore the  $\partial_z^2 f$  term

$$(\partial_r^2 f + \frac{1}{r} \partial_r f) g e^{-ikz} + 2(\partial_z f) \partial_z (g e^{-ikz}) + f \partial_z^2 (g e^{-ikz}) - \frac{1}{c^2} f \partial_t^2 (g e^{-ikz}) = 0$$

$$(\partial_r^2 f + \frac{1}{r} \partial_r f - 2ik \partial_z f) g e^{-ikz} + 2(\partial_z f) e^{-ikz} \partial_z g + f \partial_z^2 (g e^{-ikz}) - \frac{1}{c^2} f \partial_t^2 (g e^{-ikz}) = 0$$

$$(\partial_r^2 f + \frac{1}{r} \partial_r f - 2ik \partial_z f) g e^{-ikz} + f \left[ 2 \frac{\partial_z f}{f} e^{-ikz} \partial_z g + \partial_z^2 (g e^{-ikz}) - \frac{1}{c^2} \partial_t^2 (g e^{-ikz}) \right] = 0.$$

The first term is zero since  $f$  is a solution, so we must have the second term also equal to zero

$$2\frac{\partial_z f}{f} e^{-ikz} \partial_z g + \partial_z^2 (g e^{-ikz}) - \frac{1}{c^2} \partial_t^2 (g e^{-ikz}) = 0$$

$$2\frac{\partial_z f}{f} e^{-ikz} \partial_z g + (\partial_z^2 g) e^{-ikz} - 2ik(\partial_z g) e^{-ikz} - k^2 g e^{-ikz} - \frac{1}{c^2} (\partial_t^2 g) e^{-ikz} = 0$$

and eliminating the exponential

$$2\frac{\partial_z f}{f} \partial_z g + \partial_z^2 g - 2ik\partial_z g - k^2 g - \frac{1}{c^2} \partial_t^2 g = 0$$

or, using  $ck = \omega$

$$2i\omega c \partial_z g + \partial_t^2 g + \omega^2 g = c^2 \partial_z^2 g + 2c^2 \frac{\partial_z f}{f} \partial_z g. \quad (2.106)$$

Based on equation (2.103) we have

$$\partial_z g = \frac{2}{c} \frac{t - \frac{z-z_F}{c}}{\tau_0^2} g \Rightarrow 2i\omega c \partial_z g = 4i\omega \frac{t - \frac{z-z_F}{c}}{\tau_0^2} g \quad (2.107)$$

$$\partial_z^2 g = -\frac{2}{c^2} \frac{1}{\tau_0^2} g + \frac{4}{c^2} \left( \frac{t - \frac{z-z_F}{c}}{\tau_0^2} \right)^2 g \Rightarrow c^2 \partial_z^2 g = -2 \frac{1}{\tau_0^2} g + 4 \left( \frac{t - \frac{z-z_F}{c}}{\tau_0^2} \right)^2 g \quad (2.108)$$

$$\partial_t g = \left( i\omega - 2 \frac{t - \frac{z-z_F}{c}}{\tau_0^2} \right) g \quad (2.109)$$

$$\partial_t^2 g = -2 \frac{1}{\tau_0^2} g + \left( i\omega - 2 \frac{t - \frac{z-z_F}{c}}{\tau_0^2} \right)^2 g = -4i\omega \frac{t - \frac{z-z_F}{c}}{\tau_0^2} g - 2 \frac{1}{\tau_0^2} g - \omega^2 g + 4 \left( \frac{t - \frac{z-z_F}{c}}{\tau_0^2} \right)^2 g \quad (2.110)$$

Summing everything up, we still remain with a

$$\frac{\partial_z f}{f} \partial_z g = 0, \quad (2.111)$$

which is true under the paraxial approximation.

It is important to mention that this profile is not always usable. According to Quesnel and Mora 1998 finite pulse effects are important for  $c\tau_0 \lesssim 2w_0$ , and in this situation we must put an additional  $2\partial_z g \partial_z \mathbf{E}$  in the paraxial wave equation.

## The Final Fields

The final relations are straightforward

$$\mathbf{E}(r, z, t) = \mathbf{E}(r, z) g(t, z) \quad (2.112a)$$

$$\mathbf{B}(r, z, t) = \mathbf{B}(r, z) g(t, z). \quad (2.112b)$$

### 2.2.6 Laguerre-Gauss Beams

This type of beam represents a correction for the Gauss one in order to remove the axial symmetry approximation. That is, we want to find a function  $f(r, z, \varphi) = \zeta(r, z)s(r, z, \varphi)$  to be a solution of

$$\partial_r^2 f + \frac{1}{r} \partial_r f + \frac{1}{r} \partial_\varphi^2 f - 2ik \partial_z f = 0, \quad (2.113)$$

where  $\zeta$  is found in (2.93). Actually, we would rather make an educated guess for a trial solution

$$f(r, z, \varphi) = \zeta(r, z)S(r) e^{im\varphi}, \quad (2.114)$$

with  $m$  can be a real number. In this case, it is straightforward to find that  $S(r)$  turns out to satisfy an equation similar to that of the associated Laguerre polynomials. One can reach through not so short computations the expression

$$S(r) = \left( \frac{\sqrt{2r}}{w(z)} \right)^m L_{pm} \left( \frac{2r^2}{w^2(z)} \right) \exp \left( i(2p + m) \arctan \left( \frac{z}{z_0} \right) \right). \quad (2.115)$$

The associated (or sometimes also called generalized) Laguerre polynomials are a solution of (Abramowitz and Stegun 2013)

$$x L_{pm}''(x) + (m + 1 - x) L_{pm}'(x) + p L_{pm}(x) = 0, \quad (2.116)$$

where  $p \in \mathbb{N}$  and  $m \in \mathbb{R}$ . Their expression can be obtained using the Rodrigues formula

$$L_{pm}(x) = \frac{x^{-m} e^x}{p!} \frac{d^p}{dx^p} (e^{-x} x^{m+p}). \quad (2.117)$$

We will now apply the same normalization criterion we used for the Gauss mode for  $f(r, z, \varphi)$

$$\pi w_0^2 = \iint dr d\varphi r |f|^2. \quad (2.118)$$

The integration is done as such

$$\begin{aligned} \iint dr d\varphi r |f|^2 &= 2\pi \int dr r |\zeta|^2 |S|^2 = 2\pi |G(0)|^2 \left( \frac{w_0}{w} \right)^2 \int dr r e^{-\frac{2r^2}{w^2}} \left( \frac{2r^2}{w^2} \right)^m L_{pm}^2 \left( \frac{2r^2}{w^2} \right) = \\ &= \frac{1}{2} \pi |G(0)|^2 \left( \frac{w_0}{w} \right)^2 w^2 \int d \left( \frac{2r^2}{w^2} \right) e^{-\frac{2r^2}{w^2}} \left( \frac{2r^2}{w^2} \right)^m L_{pm}^2 \left( \frac{2r^2}{w^2} \right) = \\ &= \frac{\pi w_0^2}{2} |G(0)|^2 \int_0^\infty dx x^m e^{-x} L_{pm}^2(x). \end{aligned}$$

The remaining integral is trivial if we take a look at the orthogonality relation of the associated Laguerre polynomials

$$\int_0^\infty dx x^m e^{-x} L_{pm}(x) L_{p'm}(x) = \frac{(p+m)!}{p!} \delta_{pp'}. \quad (2.119)$$

This gives the result

$$G(0) = \sqrt{2} \sqrt{\frac{p!}{(p+m)!}}. \quad (2.120)$$

The final expressions for the electric field, after dealing with normalization, are simply

$$E_x^{pm}(r, z, \varphi) = E_x(r, z) \sqrt{\frac{p!}{(|m|+p)!}} \left( \frac{\sqrt{2}r}{w(z)} \right)^{|m|} L_{p|m|} \left( \frac{2r^2}{w^2(z)} \right) \exp \left( i(2p + |m|) \arctan \left( \frac{z}{z_0} \right) \right) e^{-im\varphi} \quad (2.121a)$$

$$E_y^{pm}(r, z, \varphi) = E_y(r, z) \sqrt{\frac{p!}{(|m|+p)!}} \left( \frac{\sqrt{2}r}{w(z)} \right)^{|m|} L_{p|m|} \left( \frac{2r^2}{w^2(z)} \right) \exp \left( i(2p + |m|) \arctan \left( \frac{z}{z_0} \right) \right) e^{-im\varphi} \quad (2.121b)$$

$$E_z^{pm}(r, z, \varphi) = -\frac{i}{k} \left( \partial_x E_x^{pm}(r, z, \varphi) + \partial_y E_y^{pm}(r, z, \varphi) \right), \quad (2.121c)$$

where  $E_x(r, z)$  and  $E_y(r, z)$  are to be taken from the Gaussian beam (2.97). For the sake of use in numerical simulations (mainly to eliminate the need for numerical differentiation) the  $z$  component of the field can be computed explicitly to be

$$E_z^{pm} = -\frac{i}{k} \left( -2 \frac{1 + i \frac{z}{z_0}}{w^2(z)} + \frac{L'_{p|m|} \left( \frac{2r^2}{w^2(z)} \right)}{L_{p|m|} \left( \frac{2r^2}{w^2(z)} \right)} \right) (x E_x^{pm} + y E_y^{pm}) - \frac{i}{k} \sqrt{\frac{p!}{(|m|+p)!}} \left( \frac{\sqrt{2}}{w(z)} \right)^{|m|} L_{p|m|} \left( \frac{2r^2}{w^2(z)} \right) \exp \left( i(2p + |m|) \arctan \left( \frac{z}{z_0} \right) \right) (A_x E_x + A_y E_y), \quad (2.122)$$

with

$$A_x = \begin{cases} l(x - iy)^{l-1}, & l > 0 \\ 0, & l = 0 \\ -l(x + iy)^{-l-1}, & l < 0 \end{cases} \quad (2.123a)$$

$$A_y = \begin{cases} -il(x - iy)^{l-1}, & l > 0 \\ 0, & l = 0 \\ -il(x + iy)^{-l-1}, & l < 0. \end{cases} \quad (2.123b)$$

The magnetic field is derived exactly as in the case of the Gaussian beam

$$B_x(r, z, \varphi) = -\frac{1}{c} E_y(r, z, \varphi) \quad (2.124a)$$

$$B_y(r, z, \varphi) = \frac{1}{c} E_x(r, z, \varphi) \quad (2.124b)$$

$$B_z(r, z, \varphi) = -\frac{i}{ck} [\partial_y E_x(r, z, \varphi) - \partial_x E_y(r, z, \varphi)]. \quad (2.124c)$$

The explicit third component of  $\mathbf{B}$  is

$$B_z^{pm} = -\frac{i}{ck} \left( -2 \frac{1 + i \frac{z}{z_0}}{w^2(z)} + \frac{L'_{p|m|} \left( \frac{2r^2}{w^2(z)} \right)}{L_{p|m|} \left( \frac{2r^2}{w^2(z)} \right)} \right) (y E_x^{pm} - x E_y^{pm}) - \frac{i}{ck} \sqrt{\frac{p!}{(|m| + p)!}} \left( \frac{\sqrt{2}}{w(z)} \right)^{|m|} L_{p|m|} \left( \frac{2r^2}{w^2(z)} \right) \exp \left( i(2p + |m|) \arctan \left( \frac{z}{z_0} \right) \right) (A_y E_x - A_x E_y). \quad (2.125)$$

These expressions are easier to derive if we bring together the terms  $\left( \frac{\sqrt{2}r}{w(z)} \right)^{|m|}$  and  $e^{-im\varphi}$  and replace  $r e^{\pm i\varphi}$  with  $x \pm iy$  before computing the derivatives. This step also helps to eliminate the apparent singularity that might appear on the  $z$ -axis. Also, it might be useful to write the derivative of the associated Laguerre polynomial as

$$L'_{p|m|} \left( \frac{2r^2}{w^2(z)} \right) = \begin{cases} -\frac{4}{w^2(z)} L'_{p-1,|m|+1} \left( \frac{2r^2}{w^2(z)} \right), & 1 \leq p \\ 0, & \text{otherwise} \end{cases} \quad (2.126)$$

Of course, in order to use these relations in simulations involving laser beams, one must attach also the temporal profile (2.103).

## 2.2.7 Other Types of Gauss Beams

One can only work in Cartesian coordinates in order to solve the paraxial wave equation. This will lead to obtaining the rectangular Gauss beam mode. The extension of this solution, in the same manner used to extend the cylindrical mode to the Laguerre-Gauss mode, is the Hermite-Gauss beam and, as the name suggests, uses the Hermite polynomials. However, these modes are not of interest in our endeavours. If the reader is interested to look upon them, the book by Goldsmith 1998 has a very concise and straightforward presentation of them in its first chapter.

## 2.2.8 Bessel Beams

## 2.3 Angular Momentum of Electromagnetic Waves

In this section I will simply mention how the orbital angular momentum can be defined. A thorough derivation of its expression for each of the presented laser profiles is a simple, but lengthy and redundant work. If one is interested in computing it in numerical simulations (which is the case for the present thesis), it can be computed from the values of the fields.

By having the electromagnetic momentum defined in (2.39), we can simply extend the expression of the angular momentum as is used in classical mechanics to our case, such that we have

$$\mathbf{J} = \varepsilon_0 \int d\mathbf{r} \, \mathbf{r} \times (\mathbf{E} \times \mathbf{B}) \quad (2.127)$$

Details about the actual derivation and how to apply this definition in particular cases is found in Belinfante 1940 and Humblet 1943.

# Chapter 3

## The Interaction Between Electromagnetic Radiation and Matter

Now that the aspects related to the formalism and theory behind the modeling of laser produced electromagnetic waves has been presented, we must naturally turn our attention towards the interaction of those wave pulses with matter. This chapter only deals with the dynamics of particles under the action of electromagnetic fields and the ponderomotive force, since these topics offer great insight and intuition for the physical behaviour of high intensity laser-plasma interaction. The specific phenomena arising from the properties of plasma as a medium are to be presented later.

### 3.1 Electron Dynamics in Electromagnetic Fields

This section deals with analyzing the motion of a single electron in the fields of a wave. For simplicity, I will only talk about the case of linearly polarized plane waves, since this entire discussion has the purpose of building up intuition and getting a feel for the scale of the relevant quantities. Most of what is to be presented is following the lecture notes of Karsch 2018.

The fact that we want to study dynamics and we are using a very simple type of wave means that it is actually more convenient this time around to work with real fields, rather than complex ones. As per usual, the direction of propagation is chosen to be the z-axis such that the fields are

$$\mathbf{E} = \mathbf{e}_x E_0 \cos(kz - \omega t) \quad (3.1a)$$

$$\mathbf{B} = \mathbf{e}_y B_0 \cos(kz - \omega t). \quad (3.1b)$$

Just as an exercise, it can be observed that these fields are generated by the following choice for the 4-potential

$$\begin{cases} \phi = 0 \\ \mathbf{A} = \mathbf{e}_x A_0 \sin(kz - \omega t), \end{cases} \quad (3.2)$$

where  $A_0 = \frac{E_0}{\omega} = \frac{B_0}{k}$ .

#### 3.1.1 Classical Treatment

We start from the classical equation of motion given by Newton's second principle using the Lorentz force

$$\frac{d\mathbf{p}}{dt} = \frac{d(m_e \mathbf{v}_e)}{dt} = -e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) , \quad (3.3)$$

with  $m_e$  and  $\mathbf{v}_e$  the mass and the velocity of the electron, respectively, and  $e$  the elementary charge. Since we have  $B \propto \frac{E}{c}$  and also  $v_e \ll c$  (which is implied in order to have a classical treatment), we can safely remove the second term in the right-hand side of the equation above, remaining with

$$\frac{d\mathbf{v}_e}{dt} = -\frac{e}{m_e} \mathbf{E} = -\frac{e}{m_e} E_0 \mathbf{e}_x \cos(kz - \omega t) . \quad (3.4)$$

Simply integrating with initial conditions  $x_0, y_0, z_0 = 0$  and  $\mathbf{v}_e(\mathbf{0}) = \mathbf{0}$  leads to

$$\mathbf{v}_e(t) = \frac{e}{\omega m_e} E_0 \mathbf{e}_x \sin(kz - \omega t) \quad (3.5a)$$

$$x(t) = \frac{e}{\omega^2 m_e} E_0 [\cos(kz - \omega t) - 1] . \quad (3.5b)$$

It is important now to see when the classical treatment breaks down. Let us impose that

$$v_e^{max} = c , \quad (3.6)$$

such that we have

$$a_0 \equiv \frac{eE_0}{\omega m_e c} = \frac{eA_0}{m_e c} = 1 . \quad (3.7)$$

The parameter  $a_0$  is called the normalized or dimensionless vector potential. From its definition it is easy to see that it can only take values between 0 and 1. We can use it to describe the amplitude of the electric field as such

$$E_0 = a_0 \frac{\omega m_e c}{e} . \quad (3.8)$$

It is very convenient in practice to use the wavelength and to extract the rest mass to charge ratio of the electron as follows

$$E_0 = \frac{a_0}{\lambda} 2\pi \frac{m_e c^2}{e} = \frac{a_0}{\lambda} 2\pi \cdot 511 \text{keV} . \quad (3.9)$$

The normalized vector field holds also an important significance. One can see that its definition actually boils down to

$$a_0 = \frac{v_{max}^{classical}}{c} , \quad (3.10)$$

so we can use it to find a boundary for the validity of the classical treatment. For simplicity, let's dissect the  $a_0 = 1$  case, for which the motion should be completely relativistic, keeping in mind that the classical description stops being reliable well before that. From the result concerning the Poynting vector of a plane wave (2.60), we can find the intensity of the pulse in this limiting case to be

$$I = c \frac{\varepsilon_0}{2} E_0^2 \propto \frac{a_0^2}{\lambda^2} 10^{18} \text{W} \frac{\mu\text{m}^2}{\text{cm}^2} , \quad (3.11)$$

which says that already at intensities of  $10^{18} \frac{\text{W}}{\text{cm}^2}$  the motion of the electron should be treated completely within the grounds of special relativity.

### 3.1.2 Relativistic Treatment

In the light of our discussion in the previous subsection, we see that in order to study how electrons interact with high-intensity laser beams (namely, terawatt and petawatt lasers), we should do all our calculations relativistically. The equation of motion remains the same, but the relativistic momentum is  $\mathbf{p} = \gamma m_e \mathbf{v}_e$ , where  $\gamma$  is the usual Lorentz factor. By taking the scalar product of equation (3.3) with  $\mathbf{p}$  we get

$$\frac{1}{2} \frac{d\mathbf{p}^2}{dt} = -e\mathbf{p} \cdot \mathbf{E}, \quad (3.12)$$

where we used the fact that  $\mathbf{p} \cdot (\mathbf{v}_e \times \mathbf{B})$ , since  $\mathbf{p}$  is proportional to  $\mathbf{v}_e$ . Now, it is useful to write the Lorentz factor in terms of momentum like this

$$\gamma = \frac{1}{\sqrt{1 - \frac{\mathbf{v}^2}{c^2}}} \Rightarrow \frac{1}{\gamma^2} = 1 - \frac{\mathbf{v}^2}{c^2} = 1 - \frac{1}{\gamma^2} \frac{\mathbf{p}^2}{m_e^2 c^2} \Rightarrow \gamma = \sqrt{1 + \left( \frac{\mathbf{p}}{m_e c} \right)^2}.$$

Now we can expect to find a  $\frac{d\mathbf{p}^2}{dt}$  by taking the derivative of  $\gamma$  with respect to time

$$\begin{aligned} \frac{d\gamma}{dt} &= \frac{d}{dt} \sqrt{1 + \left( \frac{\mathbf{p}}{m_e c} \right)^2} = \frac{1}{\sqrt{1 + \left( \frac{\mathbf{p}}{m_e c} \right)^2}} \frac{1}{m_e^2 c^2} \frac{1}{2} \frac{d\mathbf{p}^2}{dt} = \frac{1}{\gamma m_e^2 c^2} \frac{1}{2} \frac{d\mathbf{p}^2}{dt} \Rightarrow \\ &\Rightarrow m_e c^2 \frac{d\gamma}{dt} = -e \frac{\mathbf{p}}{\gamma m_e} \cdot \mathbf{E} = -e \mathbf{v}_e \cdot \mathbf{E}. \end{aligned}$$

Remembering that the kinetic energy in special relativity is obtained as  $K = (\gamma - 1)m_e c^2$ , we can reach an equation for it

$$\frac{dK}{dt} = -e \mathbf{v}_e \cdot \mathbf{E}. \quad (3.13)$$

This equation can also be rewritten as

$$\frac{d\gamma}{dt} = -\frac{eE_0}{m_e c} \frac{\mathbf{v}_e \cdot \mathbf{e}_x}{c} \cos(kz - \omega t) = -a_0 \omega \frac{v_x}{c} \cos(kz - \omega t). \quad (3.14)$$

In order to proceed, we should also take a better look at the equation of motion as it is

$$\begin{aligned} \frac{d}{dt} \left( \frac{\mathbf{p}}{m_e c} \right) &= -\frac{e}{m_e c} [E_0 \mathbf{e}_x + B_0 \mathbf{v} \times \mathbf{e}_y] \cos(kz - \omega t) = \\ &= -\frac{eE_0}{m_e c} \left[ \mathbf{e}_x + \frac{\mathbf{v}}{c} \times \mathbf{e}_y \right] \cos(kz - \omega t) = \\ &= -a_0 \omega \left[ \left( 1 - \frac{v_z}{c} \right) \mathbf{e}_x + \frac{v_x}{c} \mathbf{e}_z \right] \cos(kz - \omega t). \end{aligned}$$



By defining  $\tilde{\mathbf{p}} = \frac{\mathbf{p}}{m_e c}$  to be the normalized momentum, we can write the equations for its components as follows

$$\frac{d\tilde{p}_x}{dt} = -a_0\omega \left(1 - \frac{v_z}{c}\right) \cos(kz - \omega t) \quad (3.15a)$$

$$\frac{d\tilde{p}_y}{dt} = 0 \quad (3.15b)$$

$$\frac{d\tilde{p}_z}{dt} = -a_0\omega \frac{v_x}{c} \cos(kz - \omega t). \quad (3.15c)$$

The  $y$  is trivial, and since we took the initial velocity to be zero, the  $y$ -velocity will be zero at all times.

From equations (3.14) and (3.15c) we have the following developement

$$\frac{d(\tilde{p}_z - \gamma)}{dt} = 0 \Leftrightarrow \tilde{p}_z - \gamma = C. \quad (3.16)$$

Again, making use of our choice of initial conditions, which translate here as  $\gamma(0) = 1$  and  $\tilde{p}_z(0) = 0$ , we obtain  $C$  to be -1.

To summarize so far, we already know that

$$\tilde{p}_y = 0 \quad (3.17a)$$

$$\tilde{p}_z = \gamma - 1. \quad (3.17b)$$

By squaring up the very last equation, yet another useful relation can be derived

$$\gamma = 1 + \tilde{p}_z = \sqrt{1 + \tilde{\mathbf{p}}^2} \Rightarrow 1 + 2\tilde{p}_z + \tilde{p}_z^2 = 1 + \tilde{p}_x^2 + \tilde{p}_y^2 + \tilde{p}_z^2$$

$$\tilde{p}_z = \frac{1}{2}\tilde{p}_x^2. \quad (3.18)$$

Since  $p_z$  is the normalized momentum along the propagation direction of the wave, we can see that for  $\tilde{p}_z = \frac{1}{2}\tilde{p}_x^2 \ll 1$  (classical regime) the transversal momentum is more important, while for  $\tilde{p}_z = \frac{1}{2}\tilde{p}_x^2 \gg 1$  (highly relativistic regime) the longitudinal momentum is more important.

Now we would like to find  $p_x$ . There is actually a more efficient way to do so than solving equations (3.15a) and (3.15c) together. But for that we shall make use of the electromagnetic potential (3.2). We also need the relations that define the fields from the potential, as detailed in section (2.1.3). With this in mind, we return to the equation of motion

$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) = -e(-\partial_t \mathbf{A} + \mathbf{v}_e \times (\nabla \times \mathbf{A})). \quad (3.19)$$

We make use of the vector identity

$$\mathbf{v} \times (\nabla \times \mathbf{u}) = \nabla(\mathbf{v} \cdot \mathbf{u}) - (\mathbf{v} \cdot \nabla)\mathbf{u}, \quad (3.20)$$

and the total derivative of  $A$  with respect to time

$$\frac{d\mathbf{A}}{dt} = \partial_t \mathbf{A} + \partial_{x_i} A^{x_i} \partial_t x_i = \frac{\partial \mathbf{A}}{\partial t} + (\mathbf{v}_e \cdot \nabla)\mathbf{A}. \quad (3.21)$$

Thus,

$$\frac{d\mathbf{p}}{dt} = -e \left[ -\frac{d\mathbf{A}}{dt} + (\mathbf{v}_e \cdot \nabla)\mathbf{A} + \nabla(\mathbf{v}_e \cdot \mathbf{A}) - (\mathbf{v}_e \cdot \nabla)\mathbf{A} \right] = -e \left[ -\frac{d\mathbf{A}}{dt} + \nabla(\mathbf{v}_e \cdot \mathbf{A}) \right]. \quad (3.22)$$

Since

$$\frac{d\mathbf{A}}{dt} = -\mathbf{e}_x \omega A_0 \cos(kz - \omega t)$$

$$\nabla(\mathbf{v}_e \cdot \mathbf{A}) = \mathbf{e}_z k v_x A_0 \cos(kz - \omega t),$$

we can extract the  $p_x$  equation

$$\frac{dp_x}{dt} = -e\omega A_0 \cos(kz - \omega t) = e \frac{dA}{dt}, \quad (3.23)$$

which gives

$$p_x = eA + C'. \quad (3.24)$$

With the initial conditions this becomes

$$p_x = eA = eA_0 \sin(kz - \omega t). \quad (3.25)$$

Bringing together equations (3.17b), (3.18) and (3.25), using the normalized vector potential  $a = \frac{eA_0}{m_e c} \sin(kz - \omega t)$

$$K = (\gamma - 1)m_e c^2 = \frac{a^2}{2} m_e c^2 \Rightarrow \gamma = 1 + \frac{a^2}{2}. \quad (3.26)$$

With this, all the puzzle pieces are in place, so we can collect the following results concerning the motion of the electron

$$\gamma = 1 + \frac{a^2}{2} \quad (3.27a)$$

$$\tilde{p}_x = a \quad (3.27b)$$

$$\tilde{p}_y = 0 \quad (3.27c)$$

$$\tilde{p}_z = \frac{a^2}{2}. \quad (3.27d)$$

It is more convenient, and general, to work with the derivative with respect to  $\tau = t - \frac{z(t)}{c}$ , which is to choose the convenient reference frame of the wave to simplify the computations. This derivative is developed as such

$$\frac{d}{dt} = \frac{d\tau}{dt} \frac{d}{d\tau} = \left(1 - \frac{1}{c} \frac{dz}{dt}\right) \frac{d}{d\tau} = \left(1 - \frac{a^2}{2}\right) \frac{d}{d\tau} = \frac{1}{\gamma} \frac{d}{d\tau}. \quad (3.28)$$

We can also write the phase of  $a$  in terms of this time

$$kz - \omega t = kz - \omega\tau - \frac{\omega}{c}z = -\omega\tau. \quad (3.29)$$

A simple substitution gives the equations for the coordinates

$$\frac{dx}{d\tau} = ca \quad (3.30a)$$

$$\frac{dy}{d\tau} = 0 \quad (3.30b)$$

$$\frac{dz}{d\tau} = c \frac{a^2}{2}, \quad (3.30c)$$

which have the solutions (of course using the initial conditions we chose at the beginning)

$$x(\tau) = \frac{ca_0}{\omega} [\cos(\omega\tau) - 1] \quad (3.31a)$$

$$y(\tau) = 0 \quad (3.31b)$$

$$z(\tau) = \frac{ca_0^2}{4} \left[ \tau - \frac{1}{2\omega} \sin(2\omega\tau) \right]. \quad (3.31c)$$

These results show us that the motion in the transversal plane is the same as in the classical motion. However, the motion on the propagation direction is more complex, being a superposition of an oscillation and a drift motion. The drift velocity  $v_{drift} = \langle v_z \rangle = \left\langle \frac{z}{t} \right\rangle$  can be computed fairly easy

$$\begin{aligned} z_{drift} &= \frac{ca_0^2}{4} \tau = \frac{ca_0^2}{4} \left( t - \frac{z}{c} \right) = \frac{ca_0^2}{4} t - \frac{a_0^2}{4} z_{drift} \\ z_{drift} &= \frac{ca_0^2}{4} \frac{t}{1 + \frac{a_0^2}{4}} = \frac{ca_0^2}{4 + a_0^2} t \\ v_{drift} &= \frac{ca_0^2}{4 + a_0^2}. \end{aligned} \quad (3.32)$$

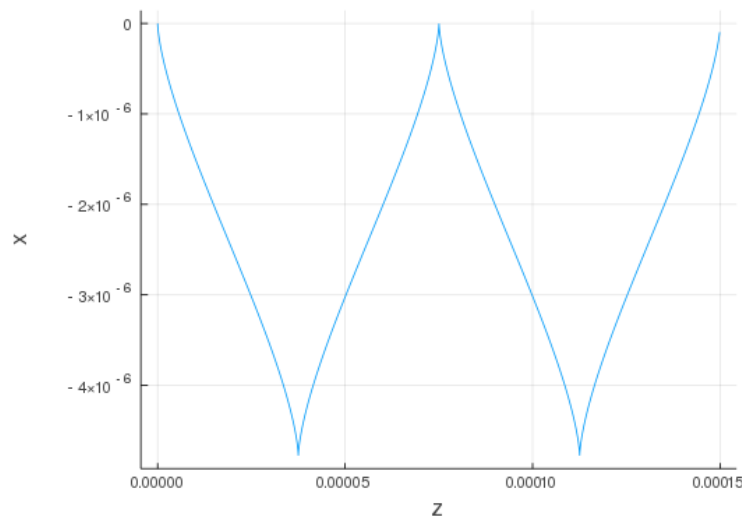


Figure 3.1: The motion in the laboratory frame over two periods of the pulse for some practical parameters:  $a_0 = 20$  and  $\nu = \frac{\omega}{2\pi} = 400$  THz

In finite length pulses, a certain phenomenon occurs. In order to obtain a finite plane wave pulse, we simply add a Gaussian envelope

$$a(\tau) = a_0 \exp\left(-\left(\frac{\tau}{\tau_0}\right)^2\right) \sin(\omega\tau). \quad (3.33)$$

Under the fields given by this potential, the electron starts moving, but it stops when the wave passes it. Thus, although the electron is moved forward, the net energy gain in its interaction with the field is zero. The theoretical calculations that prove this are quite lengthy, so, in order to visualize this effect, I offer a numerical solution of this motion solved using a standard Euler method in figure 3.2. We can see that the trajectory of the electron converges to a point after a time longer than the pulse duration.

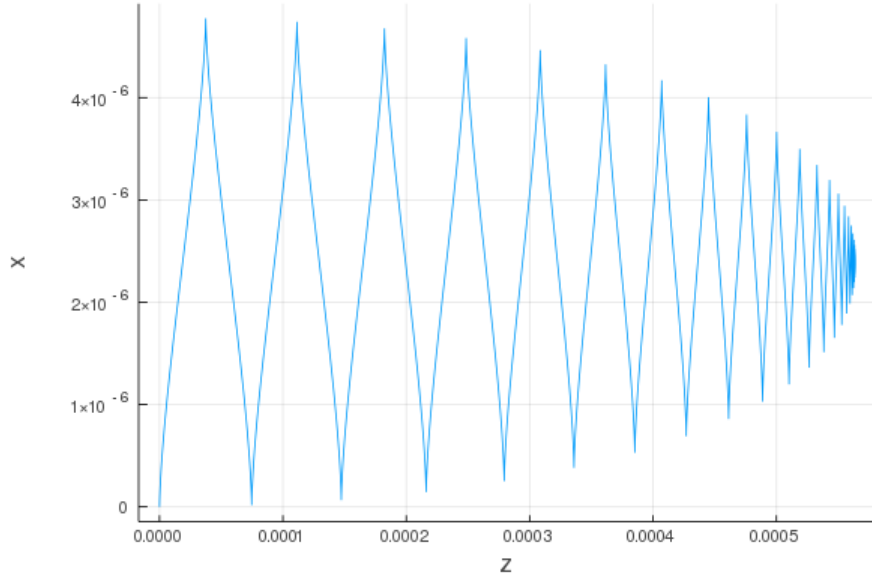


Figure 3.2: The motion in the laboratory frame over a long time compared to the pulse duration  $\tau_0$ . The parameters used were:  $a_0 = 20$ ,  $\tau_0 = 30$  fs and  $\nu = \frac{\omega}{2\pi} = 400$  THz

## 3.2 The Ponderomotive Force

## 3.3 Simulations for the Visualization of the Ponderomotive Force

## 3.4 Laser Wakefield Acceleration

# Chapter 4

## Plasma Physics

### 4.1 The Definition of Plasma

It is common that people, when asked about what is plasma, their definition stops at the fact that it is a **partially ionized gas**. But this is just one of the three defining characteristics. After all, even the air is partially ionized. The other two properties that a medium should satisfy in order to be considered plasma are quasi-neutrality and collective behaviour.

To be **quasi-neutral** means that the medium has an equal number of positive and negative charges in its entire volume, but small deviations from neutrality are possible locally. That is, if  $n_p$ ,  $n_e$  are the positive charge density and the electron density, respectively, in the whole region of the plasma we have  $n_p = n_e$ , yet in small regions in the space inside we have  $n_p \approx n_e$ . A small remark should be made here. While I say that the plasma as a whole is neutral, it is so by approximation still. If one starts building plasma by pumping energy into a gaseous medium for example, some of the first ionized electrons can actually escape the medium. It is only after a certain positive charge density has been achieved that no electrons can not escape anymore due to Coulomb attraction. Once enough ionization electrons are produced, the charge imbalance becomes incredibly small (*i.e.*  $\frac{n_p - n_e}{n_e} \ll 1$ ). This is though a very hard to observe charge imbalance in practice, so we can say that plasma as a whole is neutral. The localized imbalance in turn is not constantly small; it can vary widely due to the disordered motion of the constituent particles, but statistically speaking neutrality is maintained locally when we look at the time averages.

**Collective behaviour** is a consequence of the fact that the main type of interaction between the particles constituting the plasma, namely Coulomb interaction, is long range. As such, we can say that any particle in the plasma feels all the other ones. This leads to many important properties specific to plasma, like particle and momentum transport. The simplest response is plasma oscillation, which arises when plasma is placed in a constant electric field. The electrons are pushed by the electric field, but the surplus of positive charge left behind pulls them back, creating an oscillatory motion (we should take into consideration that the positive ions are at least a couple thousand times heavier than the electrons, so it is harder to influence their motion). This property also influences the way in which plasma interacts with electromagnetic radiation, giving rise to radiation transport phenomena for example.

It is important to note from the very beginning that in a plasma we have quite many different species of particles. The most simple model would only include electrons, neutral atoms and ions that have just one missing electron, but in reality we can have all the possible types of ions (so also with two or more missing electrons) and photons (which arise from the excitations and de-excitations that happen in this very energetic medium).

In the following sections we aim to go deeper into the parameters that characterize plasmas and the basic models for it. The discussion brings together ideas from Karsch 2018 and Mulser and Bauer 2010.

## 4.2 Temperature

We would like now to study the statistics of electrons. First of all, we should realize that the interparticle distances in plasmas are quite large, but also the temperature needed to sustain ionization is quite high. So high in fact that working with the Fermi-Dirac statistics is not necessary, since this quantum mechanically derived distribution can be approximated very well by the classical Maxwell-Boltzmann distribution in this particular situation.

The number of electron with x-axis velocity between  $v_{e,x}$  and  $v_{e,x} + dv_{e,x}$  is then given by

$$f_e(v_{e,x}) dv_{e,x} = n_e \sqrt{\frac{m_e}{2\pi K_B T_e}} e^{-\frac{K_x}{K_B T_e}}, \quad (4.1)$$

where  $n_e$ ,  $m_e$  and  $T_e$  are the electrons' density, mass and temperature, respectively,  $K_B$  is the Boltzmann constant and  $K_x = \frac{m_e v_{e,x}^2}{2}$  is the kinetic energy of the photons. The normalization constant was obtained from the electron density, since  $n_e = \int_{-\infty}^{+\infty} dv_{e,x} f_e(v_{e,x})$ . This gives an average kinetic energy of

$$K_x^{avg} = \frac{\int_{-\infty}^{+\infty} dv_{e,x} K_x f_e(v_{e,x})}{\int_{-\infty}^{+\infty} dv_{e,x} f_e(v_{e,x})} = \frac{m_e}{2n_e} \int_{-\infty}^{+\infty} dv_{e,x} v_{e,x}^2 f_e(v_{e,x}) = \frac{1}{2} K_B T_e. \quad (4.2)$$

This is extended in 3D easily, since the distribution of velocity in this case should not have any preferential direction

$$K^{avg} = \frac{3}{2} K_B T_e. \quad (4.3)$$

As it can be seen, we can basically treat the electrons inside the plasma as we would an ideal gas and we have obtained that the average kinetic energy is proportional to the temperature.

A simple numerical application shows us that in order to have  $K_B T_e = 1$  eV, the temperature would be around 11600 K. Thus, since the ionized electrons are above the energy level of outer bounded states (so above 1 eV), using Kelvin or degrees Celsius is not that handy. In practice, we will rather use eV (energy units) temperature, which is to be converted to the usual temperature by dividing to  $K_B$ .

We could actually treat the ions and the neutral atoms inside the plasma in the same manner. Considering this, we must make the remark that we can have different temperature scales in plasmas. While at thermodynamic equilibrium the system of electrons, ions and neutrals should have a uniform temperature, under the action of an electric field, lets say, the motion of the electrons is influenced more than that of the ions due to the difference in mass, while the neutrals are not affected at all, so we have  $T_n \neq T_i \neq T_e$ . Of course, equilibration between species can be achieved through collisions or radiation emission and absorption. In complete models, one should also consider the temperatures of photons and individual ion subspecies that can appear. Considering this, in general, thermal equilibration can take a long time. It is also important to visualize that the temperature can be directionally dependent depending on the orientation of the fields we apply.

### 4.3 Debye Shielding

In this section we will derive a common criterion for quasi-neutrality. Let us consider an infinite medium filled with plasma at thermal equilibrium,  $T = T_e = T_i$  and with one ion species with charge  $Ze$ , such that we have  $n_e = Zn_i$ . We are interested to see what happens if we introduce an infinite plane with constant positive surface charge density  $\sigma$  in this system (see figure 4.1).

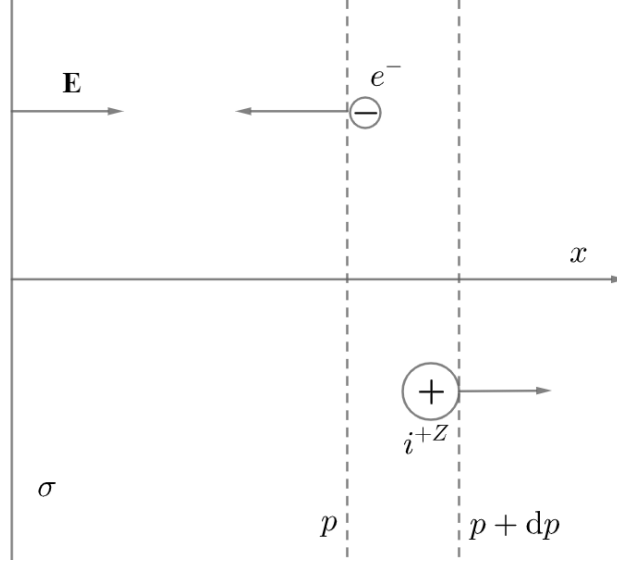


Figure 4.1: A schematic figure that shows the action of introducing the charged sheet in the plasma

The constant electric  $E = \frac{\sigma}{2\epsilon_0}$  generated by the plate will act to locally separate sheets of electrons and ions, until equilibrium between the pressures  $p_e = n_e K_B T$  and  $p_i = n_i K_B T$  is achieved. For the electrons in a sheet of thickness  $\delta x$  we have

$$dp_e = K_B T dn_e = -en_e E \delta x, \quad (4.4)$$

which can be rewritten as

$$\frac{1}{n_e} \partial_x n_e = -\frac{e}{K_B T} E = \frac{e}{K_B T} \partial_x \phi, \quad (4.5)$$

where  $\phi$  is the electrostatic potential. Solving this equation for the density of electrons, we obtain

$$n_e(x) = \bar{n}_e e^{\frac{e\phi}{K_B T}}, \quad \bar{n}_e = n_e(x \rightarrow \infty). \quad (4.6)$$

In the same manner one obtains a similar expression for the ion density

$$n_i(x) = \frac{\bar{n}_e}{Z} e^{-\frac{Ze\phi}{K_B T}}. \quad (4.7)$$

Writing the Poisson equation in terms of these results gives us

$$\partial_x^2 \phi = \frac{e\bar{n}_e}{\epsilon_0} \left( e^{\frac{e\phi}{K_B T}} - e^{-\frac{Ze\phi}{K_B T}} \right). \quad (4.8)$$

If the potential energy arising from the field is small compared the the kinetic energy of the particles in the plasma, *i.e.*  $e\phi \ll K_B T$ , the potential equation can be simplified in approximation to

$$\partial_x^2 \phi = \frac{e\bar{n}_e}{\varepsilon_0} \left( 1 + \frac{e\phi}{K_B T} - 1 + \frac{Ze\phi}{K_B T} \right) = \frac{e^2 \bar{n}_e (Z+1)}{\varepsilon_0 K_B T} \phi. \quad (4.9)$$

Obtaining the solution if this is trivial

$$\phi(x) = \phi_0 e^{-\frac{x}{\lambda_D}}, \quad (4.10)$$

where we introduced the Debye length

$$\lambda_D = \sqrt{\frac{\varepsilon_0 K_B T}{\bar{n}_e e^2 (Z+1)}}. \quad (4.11)$$

This shows us that at a distance of  $\lambda_D$  away from the plate, the electric field generated by it, as well as the corresponding potential, is screened by about 63%. This offers us great insight in how to obtain quasi-neutrality.

From this discussion we can conclude that quasi-neutrality holds if the spatial extension of our ionized gas is at least a couple times larger than the Debye length, since in this case the local deviations from neutrality  $n_p \approx n_e$  are screened. For dimensions smaller than  $\lambda_D$ , there is no quasi-neutrality very high-intensity localized fields can occur giving rise to interesting physical phenomena.

In practice, one uses another form for  $\lambda_D$  which neglects the  $Z$  and uses the temperature and particle density with more convenient units

$$\lambda_D = \sqrt{\frac{\varepsilon_0 K_B T}{\bar{n}_e e^2}} = 6.9 \sqrt{\frac{T_e [\text{K}]}{n_e [\text{cm}^3]}}, \quad (4.12)$$

the last expression giving  $\lambda_D$  in cm.

## 4.4 Plasma Frequency

The simplest plasma wave is a longitudinal oscillation of the electrons (caused by an external electric field). Considering how heavy all the other particle species are compared to them, we can treat this problem by considering the ions stationary. Thus, the electrons simply move in a static positive background. The local changes in electron density cause imbalance and, as we mentioned before, restoring Coulombian forces arise. In what follows we will work purely electrostatic by considering that the electric field is always parallel to the x-axis and the external electric field. We also consider that the electron temperature is close to zero.

We make use of the equation of motion for a single electron, the continuity equation and the Poisson equation

$$m_e \frac{dv_x}{dt} = m_e (\partial_t v_x + v_x \partial_x v_x) = -eE \quad (4.13a)$$

$$\partial_t n_e + \partial_x (n_e v_x) = 0 \quad (4.13b)$$

$$\partial_x E = \frac{e}{\varepsilon_0} (n_p - n_e), \quad (4.13c)$$

where  $n_p$  is the positive charge density divided by the unit charge. In equation (4.13a) we can neglect the second term by considering that the velocity is small. We have  $v_x \partial_x v_x = \frac{1}{2} \partial_x v_x^2 \approx 0$ , since  $v_x^2 \ll v_x$  (remember that we work with  $T_e \approx 0$ ), so



$$\partial_t v_x = -\frac{e}{m_e} E. \quad (4.14)$$

Similarly, considering that the particle density is also slowly changing around an equilibrium position  $n_0 = n_p$  (*i.e.*  $n_e = n_0 + n(x, t)$ ), we can simplify equation (4.13b)

$$\partial_t n_e + n_0 \partial_x v_x = 0. \quad (4.15)$$

These approximations also change equation (4.13c)

$$\partial_x E = -\frac{e}{\varepsilon_0} n. \quad (4.16)$$

Using a plane wave ansatz for  $E$ ,  $v_x$  and  $n$

$$E = E_0 e^{i(kx - \omega t)} \quad (4.17a)$$

$$v_x = v_0 e^{i(kx - \omega t)} \quad (4.17b)$$

$$n = n_{10} e^{i(kx - \omega t)}, \quad (4.17c)$$

The approximated equation become

$$-i\omega v_0 = -\frac{e}{m_e} E_0 \quad (4.18a)$$

$$-i\omega n_{10} + i n_0 k v_0 = 0 \quad (4.18b)$$

$$i k E_0 = -\frac{e}{\varepsilon_0} n_{10}. \quad (4.18c)$$

The frequency  $\omega$  can be extracted from these relations as follows

$$-i\omega v_0 = -\frac{e}{m_e} E_0 = \frac{e^2}{i\varepsilon_0 k m_e} n_{10} = \frac{e^2}{i\varepsilon_0 k m_e} \frac{k n_0}{\omega} v_0, \quad (4.19)$$

or

$$\omega_p = \sqrt{\frac{n_0 e^2}{\varepsilon_0 m_e}}. \quad (4.20)$$

This is called the cold plasma frequency. This result can be used to derive the plasma waves dispersion relation for the thermal motion of electrons

$$\omega^2 = \omega_p^2 + 3k^2 \frac{K_B T_e}{m_e} = \omega_p^2 + \frac{3}{2} k^2 v_{th}^2, \quad (4.21)$$

where  $v_{th}$  is the thermal velocity. As usual, the dispersion relation is useful for finding the phase and group velocities

$$v_{ph} = \frac{\omega}{k} = \sqrt{\frac{\omega_p^2}{k^2} + \frac{3}{2} v_{th}^2} \quad (4.22a)$$

$$v_{gr} = \frac{\partial \omega}{\partial k} = \frac{3}{2} \frac{v_{th}^2}{v_{ph}}. \quad (4.22b)$$

All these velocities satisfy the inequality

$$v_{gr} < \sqrt{\frac{3}{2}} v_{th} < v_{ph} . \quad (4.23)$$

It is also important to remark that the cold plasma frequency (4.20) and the Debye length (4.12) can be related with each other

$$\omega_p \cdot \lambda_D = \sqrt{\frac{K_B T_e}{m_e}} \propto v_{th} . \quad (4.24)$$

## 4.5 Electromagnetic Waves in Plasma

We will now try to discuss how a plane wave interacts with a plasma medium. We shall start assuming that we have a wave that enters the plasma having initially the properties

$$\mathbf{E}, \mathbf{B} \propto e^{i(\mathbf{k}\mathbf{r} - \omega t)} \quad (4.25a)$$

$$\mathbf{B} = \frac{1}{c} \mathbf{k} \times \mathbf{E} . \quad (4.25b)$$

For simplicity, we will assume that no longitudinal field components arise from the interaction with the plasma. While this may not be a perfectly realistic assumption, the longitudinal components that appear would be very small and would not affect to much the result we obtain.

We will make use of the already familiar Maxwell equations (two of them, to be precise)

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2} \partial_t \mathbf{E} \Rightarrow \nabla \times (\partial_t \mathbf{B}) = \frac{1}{\varepsilon_0 c^2} \partial_t \mathbf{j} + \partial_t^2 \mathbf{E} \quad (4.26a)$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B} \Rightarrow \nabla \times (\nabla \times \mathbf{E}) = \nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} = -\nabla \times (\partial_t \mathbf{B}) . \quad (4.26b)$$

Bringing these results together gives

$$\nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} + \frac{1}{\varepsilon_0 c^2} \partial_t \mathbf{j} + \partial_t^2 \mathbf{E} = 0 . \quad (4.27)$$

From equation (4.25) we can compute the derivatives to obtain

$$i \nabla(\mathbf{k} \cdot \mathbf{E}) + k^2 \mathbf{E} - i \frac{\omega}{\varepsilon_0 c^2} \mathbf{j} - \frac{\omega^2}{c^2} \mathbf{E} = 0 . \quad (4.28)$$

Here the assumption of no longitudinal field component comes in handy and removes the first term, leaving us with

$$(\omega^2 - c^2 k^2) \mathbf{E} = -i \frac{\omega}{\varepsilon_0} \mathbf{j} . \quad (4.29)$$

We shall deviate a bit in order to find an expression for the current density. We can find the average electron velocity from the force equation

$$m_e \partial_t \mathbf{v}_e = -e \mathbf{E} \Rightarrow \mathbf{v}_e = \frac{e}{i \omega m_e} \mathbf{E} \quad (4.30)$$

and introduce it in the definition of the current density in terms of drift velocity

$$\mathbf{j} = -e n_0 \mathbf{v}_e . \quad (4.31)$$

By putting together these last three results we obtain the dispersion relation for plane electromagnetic waves in plasma

$$\omega^2 = \omega_p^2 + k^2 c^2. \quad (4.32)$$

From this, obtaining also the phase velocity is trivial

$$v_{ph} = \frac{c}{\sqrt{1 - \frac{\omega_p^2}{\omega^2}}} = \frac{c}{\eta}. \quad (4.33)$$

Here we have also defined the plasma refractive index  $\eta = \frac{kc}{\omega}$ . It gives very important criteria for propagation of waves in plasma. If  $\omega > \omega_p$ , then  $\eta < 1$  and the wave can propagate through. Otherwise, when  $\omega < \omega_p$  and  $\eta$  is imaginary, the wave can not propagate; it will drop exponentially after it enters the plasma medium. The group velocity is also obtained to be

$$v_{gr} = c\eta < c. \quad (4.34)$$

There is also a physical way to think about the possibility of propagation of a wave. If the electromagnetic oscillation occur at a faster rate than that to which the plasma can react, the charged particles in the plasma will not respond fast enough to shield the radiation and it will penetrate. In the oposite case, the incoming radiation is shielded and energy conservation dictates that the wave must be reflected. Whatever small part of the wave would enter the plasma will drop very fast.

## 4.6 The Vlasov Equation

## 4.7 Two Stream Instability

# Chapter 5

## Results

In this chapter we present the main results . . .

# Chapter 6

## Conclusions

In conclusion . . .

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