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**Physics Department**

Project of Research

# Using of Laser-Plasma Interaction for Laser Propulsion Applications

A Graduation Project Submitted to the Physics Department/ College of Science/ University of Babylon in partial Fulfilment of the Requirements for the Degree of B.Sc. in Physics

By

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**جمهورية العراق**


**وزارة التعليم العالي والبحث العلمي**

**جامعة بابل / كلية العلوم / قسم الفيزياء**


مشروع البحث

# استخدام تفاعل الليزر مع البلازما في تطبيقات الدفع بالليزر

بحث تخرج مقدم الى قسم الفيزياء/ كلية العلوم/ جامعة بابل كجزء من متطلبات نيل درجة البكالوريوس في علوم الفيزياء


إعداد الطالب

**علي لفتة ناصر لفتة**

قسم الفيزياء

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**٢٠٢٤م** **١٤٤٥هـ**

# Supervision Certification

I certify that this project research entitled **"Using of Laser-Plasma Interaction for Laser Propulsion Applications"** is under my supervision at Department of Physics/ College of Science/ University of Babylon, as a partial fulfillment of the requirements for the degree of Bachelor of Science in Physics .

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Date : / / 2024

## Certification of the Head of Department

In view of the available recommendation, I forward this project research for debate:

Signature:

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Date: / / 2024

## اقرار المشرف على البحث

اقر بأن اعداد البحث الموسوم (**استخدام تفاعل الليزر مع البلازما في تطبيقلت الدفع بالليزر**) للطالب(علي لفته ناصر لفته) قد جرى تحت اشرافي في قسم الفيزياء / كلية العلوم / جامعة بابل للعام الدراسي ٢٠٢٣ – ٢٠٢٤وهي جزء من متطلبات نيل درجة بكالوريوس علوم في الفيزياء.

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المرتبة العلمية :

التأريخ :

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بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

(( شَهِدَ اللَّهُ أَنَّهُ لا إِلَهَ إِلَّا هُوَ وَالْمَلائِكَةُ وَأُولُو الْعِلْمِ قَائِماً بِالْقِسْطِ )) .

صدق الله العلي العظيم

سورة ال عمران (18)

# الإهداء

إلـى

سَيِّد البَشَر، وخاتَمِ الرُّسُل، مُحَمَّدُ بنُ عبدِ الله (ص).

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إلـى

أُمُّ الوُجُود ، فاطِمةُ الزَّهرَاءِ (ع).

إلـى

إبنِ الصِّراطِ المُستَقِيم ، وَ بنِ النَّبَأِ العَظِيم ، وَ بنَ مَنْ هُوَ فِي أُمِّ الكِتَابِ لَدى اللهِ عَلِيٌّ حَكِيمْ. صَاحِبِ العَصرِ والزَّمان (عج).

# شكر وتقدير

الحمد لله رب العالمين والصلاة والسلام على أشرف الأنبياء والمرسلين سيدنا محمَّد وعلى آله وصحبه ومن تبعهم بإحسان إلى يوم الدين، وبعد .

أشكر الله تعالى على فضله حيث وفقني لانجاز هذا العمل بفضله، فله الحمد أولاً وآخرًا.

أتقدم بالشكر لمن فضلهما لا ينقطع عليَّ والدي الحبيبين واخواني على كل جهودهم الذي بذولها لي منذ لحظة ولادتي إلى هذه اللحظة .

و أشكر أولئك الذين مدوا لي يدَ المساعدة خلال هذه الفترة، وفي مقدمتهم أستاذتي المشرفة على البحث الدكتورة نهال عبدالله عبدالوهاب المحترمة لما كان لها فضل كبير علينا في إنجاز مشروع التخرج من خلال توجيهاتها لنا وتقديم الدعم الكبير، ويتوجب علينا أن نتوجه لها بالشكر والثناء وإن كان لا يفيها حقها إلا انه الطريق لحفظ الجميل .

وكذلك اود شكر استاذي رياض صالح مهدي لمساعدته الكبيرة في إتمام هذا البحث.

كما اشكر اساتذتي في قسم الفيزياء لما بذلوه من جهد خلال دراستي للسنوات الأربعة الماضية وادعو لهم بدوام الصحة والعافية والى كل من مد يد العون والمساعدة بقلب صادق.

وكذلك اود شكر أصدقائي الذين لطالما وقفوا بجانبي وساندوني.

# Contents

# Abstract

Plasma is the fourth state of matter after the gaseous state, which constitutes the most common state of matter in the universe. 99% of the universe is in the plasma state. They have very high temperatures, reaching millions, and are found in the interior of stars. They can also be produced industrially, such as fluorescent lamps and plasma screens.

In this research, the focus is on an exciting phenomenon that occurs when light interacts with plasma. When intense laser light is supplying to an atmosphere of plasma, there are several interactions that will occur, which are referred to as laser-plasma interactions. These interactions represent the absorption of positive and negative charges into the energy of photons coming from the laser , these particles will gain a kinetic energy and thus the possibility of accelerating them.

In the practical side of the research, an experiment was conducted to prove this phenomenon. An Ar plasma was subjected to an intense laser pulses with an output power of 500mW , then measuring the current of charges (electrons). The result was very accptable so that the current increased due to the laser pulses, thus proving this phenomenon.

This phenomenon has been exploited in several applications, including particle acceleration for high-energy physics, fusion research, laser-driven particle therapy in medicine, Laser-induced breakdown spectroscopy (LIBS), laser-based material processing (micromachining, surface modification, etc.).

# الخلاصة

البلازما هي الحالة الرابعة للمادة بعد الحالة الغازية والتي تشكل اكثر حالات المادة شيوعا في الكون ٩٩% من الكون يكون في حالة البلازما . تكون على درجات حرارية عالية جدا تصل الى الملايين وتوجد في باطن النجوم وكذلك يمكن انتتاجها صناعيا مثل مصابيح الفلورسنت وشاشات البلازما.

في هذا البحث يتم التركيز على ظاهرة مثيرة تحصل عند تفاعل الضوء مع البلازما، حيث انه عند تسليط ضوء ليزر كثيف على جو من البلازما فان هنالك عدة تفاعلات سوف تحصل يشار اليها (تفاعلات الليزر– بلازما). هذه التفاعلات تمثل امتصاص الشحنات الموجبة والسالبة لطاقة الفوتونات القادمة من الليزر و اكساب الشحنات طاقة حركية وبالتالي امكانية تعجيلها.

في الجانب العملي من البحث تم اجراء تجربة لاثبات هذه الظاهرة ، حيث تم تعريض جو من البلازما الى نبضات ليزرية بقدرة 500mW. وتم قياس تيار الشحنات(الالكترونات) وكانت النتيجة ان التيار يزداد بفعل نبضات الليزر وبالتالي اثبات هذه الظاهرة.

لقد تم استثمار هذه الظاهرة في عدة مجالات، اهم التطبيقات كانت في تعجيل الجسيمات في مجال فيزياء الطاقة العالية، في أبحاث الاندماج النووي، العلاج بالشحنات المدفوعة بالليزر في مجال الطب، التحليل الطيفي للانهيار البصري الناجم عن الليزر (LIBS) وكذلك تستثمر هذه الظاهرة في مجال معالجة المواد بالليزر.

# Chapter One

# Theoretical Part

## 1.1 Introduction

Lasers acronym of (Light Amplification by Stimulated Emission of Radiation) are devices that generate or amplify electromagnetic radiation, ranging from the long infrared region up through the visible region and extending to the ultraviolet and recently even to the x-ray region. The 1964 Nobel Prize for physics was shared between Charles Townes, Nikolai Basov and Alexander Prokhorov for their fundamental work in the 1950s that led to the construction of the laser. Laser is widely used in many applications due to its magnificent properties, the high intensity, high directionality, coherence, and small beam divergence, these are properties cannot be achieved by ordinary light, these features make lasers effective tools in many fields such as medicine, engineering, industry, and so many other applications[1].One of the magnificent applications is the Laser-Plasma Interaction. The impressive development of high power lasers over the last 30 years has given great impetus to the study of high energy density physics in the laboratory. On a bright sunny day, the power of the sun light striking the surface of the earth is about 2 Watts. With a magnifying glass, one can readily focus this sunlight to an intensity of about $10^2$ W/cm$^2$, sufficient to start a leaf burning. In comparison, the National Ignition Facility (projected for completion in 2008) will deliver over 1014 Watts of laser power, which will be focused to intensities of about 1015 W/cm2. According to calculations, this facility (NIF) can ignite a fusion burn and produce a miniature star in the laboratory.[2].

## 1.2 Literature Survey

There are many previous studies which has been investigated before starting the work, the most relevant studies are

**In (2024) Alaa Raad *et al.***[3] presented a thorough spectroscopic investigation of atmospheric- plasma generated by a plasma jet. The study examinated the plasma behavior under varying flow rates of argon gas. A primary objective is to identify the optimal flow rate that facilitates the application of the generated plasma in sterilization and bacterial eradication operations. The findings established a correlation between argon flow and critical plasma parameters, specifically noting variations in electron temperature (Te) & electron number density (ne). Crucially, the study demonstrated that lower argon flow rates are more effective in generating active species such as hydroxyl and NO reactive species. The results of this investigation hold significant promise for advancing our comprehension of plasma jet technology's utility in sterilization or medical treatment processes, emphasizing the importance of gas flow optimization for these applications.

**In (2024) J. Hornung *et al.***[4] presented the development and experimental utilization of a synchronized off-harmonic laser system designed as a probe for ultra-intense laser-plasma interaction experiments. The system exhibited a novel seed-generation design, allowing for a variable pulse duration spanning over more than three orders of magnitude, from 3.45 picoseconds to 10 nanoseconds. This makes it suitable for various plasma diagnostics and visualization techniques. In a side-view configuration, the laser was employed for interferometry and streaked shadowgraphy of a laser-induced plasma while successfully suppressing the self-emission background of the laser-plasma interaction, resulting in a signal-to-self- emission ratio of 110 for this setup. These properties enable the probe to yield valuable insights into the plasma dynamics and interactions at PHELIX and to be be deployed at various laser facilities due to its easy-to-implement design.

**In (2021) Divya Singh *et al.***[5] pointed out that these days Terahertz frequency domain of electromagnetic spectrum has emerged as a extensive tool of the technology based on their day to day applications. EM radiation with submilimeter wavelength falls in THz frequency range. The mechanism of terahertz generation from laser plasma interaction is very interesting topic of research. There are two major approach of THz radiation involve beating of laser pulses in plasma and wake field excitation. The effect of different profile of lasers on the magnitude of beat wave and wakefield is to be investigated and further theoretical description is to be presented for emission of terahertz pulses. It is also studied that how electron neutral collisions adverse the mechanism of THz emission.

**In (2018) L. Ly *et al.***[6] pointed out that the use of plasma energy has expanded in surgery and medicine. Tumor resection in surgery and endoscopy has incorporated the use of a plasma scalpel or catheter for over four decades. A new plasma energy has expanded the tools in surgery: Cold Atmospheric Plasma (CAP). A cold plasma generator and handpiece are required to deliver the CAP energy. The authors evaluated a new Cold Plasma Jet System. The Cold

Plasma Jet System consists of a USMI Cold Plasma Conversion Unit, Canady Helios Cold Plasma® Scalpel, and the Canady Plasma® Scalpel in Hybrid and Argon Plasma Coagulation (APC) modes. This plasma surgical system is designed to remove the target tumor with minimal blood loss and subsequently spray the local area with cold plasma. In this study, various operational parameters of the Canady Plasma® Scalpels were tested on ex vivo normal porcine liver tissue. These conditions included various gas flow rates (1.0, 3.0, 5.0 L/min), powers (20, 40, 60 P), and treatment durations (30, 60, 90, 120 s) with argon and helium gases. Plasma length, tissue temperature changes, and depth and eschar injury magnitude measurements resulting from treatment were taken into consideration in the comparison of the scalpels. The authors report that a new cold plasma jet technology does not produce any thermal damage to normal tissue.

## 1.3 Plasma

Plasmas are often described as the fourth state of matter, alongside gases, liquids and solids, a definition which does little to illuminate their main physical attributes. In fact, a plasma can exhibit behaviour characteristic of all three of the more familiar states, depending on its density and temperature, so we obviously need to look for other distinguishing features. A simple textbook definition of a plasma would be: a quasi-neutral gas of charged particles showing collective behaviour. This may seem precise enough, but the rather fuzzy-sounding terms of 'quasi-neutrality' and 'collectivity' require further explanation. The first of these, 'quasi-neutrality', is actually just a mathematical way of saying that even though the particles making up a plasma consist of free electrons and ions, their overall charge densities cancel each other in equilibrium. So if $n_e$ and ni are, respectively, the number densities of electrons and ions with charge state Z, then these are locally balanced, i.e.

$$n_e \approx Zn_i \quad (1)$$

The second property, 'collective' behaviour, arises because of the long-range nature of the 1/r Coulomb potential, which means that local disturbances in equilibrium can have a strong influence on remote regions of the plasma. In other words, macroscopic fields usually dominate over short-lived microscopic fluctuations, and a net charge imbalance $\rho = e(Zn_i - n_e)$ will immediately give rise to an electrostatic field according to Gauss's law,

$$\nabla \cdot E = \rho/\varepsilon_o \tag{2}$$

Likewise, the same set of charges moving with velocities ve and vi will give rise to a current density $J = e(Zn_i v_i - n_e v_e)$. This in turn induces a magnetic field according to Ampères law,

$$\nabla \times B = \mu_o J. \tag{3}$$

It is these internally driven electric and magnetic fields that largely determine the dynamics of the plasma, including its response to externally applied fields through particle or laser beams as, for example, in the case of plasma-based accelerator schemes. Now that we have established what plasmas are, it is natural to ask where we can find them. In fact they are rather ubiquitous: in the cosmos, 99% of the visible universe including stars, the interstellar medium and jets of material from various astrophysical objects is in a plasma state. Closer to home, the ionosphere, extending from around 50 km (equivalent to 10 Earth radii) to 1000 km, provides vital protection from solar radiation to life on Earth. Terrestrial plasmas can be found in fusion devices (machines designed to confine, ignite and ultimately extract energy from deuterium–tritium fuel), street lighting, industrial plasma torches and etching processes, and lightning discharges. Needless to say, plasmas play a central role in the topic of the present school, supplying the medium to support very large travelling-wave field structures for the purpose of accelerating particles to high energies. Table 1 gives a brief overview of these various plasma types and their properties. [7].

**Table 1.1:** Densities and temperatures of various plasma types.

| ***Type*** | ***Electron density*** $n_e$ $(cm^{-1})$ | ***Temperature*** $T_e$ $(eV)$ |
|---|---|---|
| *Stars* | $10^{26}$ | $2 \times 10^{3}$ |
| *Laser fusion* | $10^{25}$ | $3 \times 10^{3}$ |
| *Magnetic fusion* | $10^{15}$ | $10^{3}$ |
| *Laser-produced* | $10^{18}$–$10^{24}$ | $10^{2}$–$10^{3}$ |
| *Discharges* | $10^{12}$ | 1–10 |
| *Ionosphere* | $10^{6}$ | 0.1 |
| *Interstellar medium* | 1 | $10^{-2}$ |

## 1.4 Occurrence of Plasmas in Nature

It has often been said that 99% of the matter in the universe is in the plasma state; that is, in the form of an electrified gas with the atoms dissociated into positive ions and negative electrons. This estimate may not be very accurate, but it is certainly a reasonable one in view of the fact that stellar interiors and atmospheres, gaseous nebulae, and much of the interstellar hydrogen are plasmas. In our own neighborhood, as soon as one leaves the earth's atmosphere, one encounters the plasma comprising the Van Allen radiation belts and the solar wind. On the other hand, in our everyday lives encounters with plasmas are limited to a few examples: the flash of a lightning bolt, the soft glow of the Aurora Borealis, the conducting gas inside a fluorescent tube or neon sign, and the slight amount of ionization in a rocket exhaust. It would seem that we live in the 1% of the universe in which plasmas do not occur naturally[8].

## 1.5 Plasma Parameters

Three fundamental parameters1 characterize a plasma:

**1.** the particle density n (measured in particles per cubic meter).

**2.** the temperature T of each species (usually measured in eV, where 1 eV=11,605 K).

**3.** the steady state magnetic field B (measured in Tesla).

A host of subsidiary parameters (e.g., Debye length, Larmor radius, plasma frequency, cyclotron frequency, thermal velocity) can be derived from these three fundamental parameters. For partially-ionized plasmas, the fractional ionization and cross-sections of neutrals are also important.[9].

## 1.6 Examples of plasma

### 1.6.1 Non-Fusion terrestrial plasmas

It takes considerable resources and skill to make a hot, fully ionized plasma and so, except for the specialized fusion plasmas, most terrestrial plasmas (e.g., arcs, neon signs, fluorescent lamps, processing plasmas, welding arcs, and lightning) have electron temperatures of a few eV, and for reasons given later, have ion temperatures that are colder, often at room temperature. These ‘everyday’ plasmas usually have no imposed steady state magnetic field and do not produce significant self magnetic fields. Typically, these plasmas are weakly ionized and dominated by collisional and radiative processes. Densities in these plasmas range from $10^{14}$ to $10^{22}$ $m^{-3}$ (for comparison, the density of air at STP is $2.7 \times 10^{25}$ $m^{-3}$ )[9].

### 1.6.2 Fusin-grade terrestrial plasma

Using carefully designed, expensive, and often large plasma confinement systems together with high heating power and obsessive attention to purity, fusion researchers have succeeded in creating fully ionized hydrogen or deuterium plasmas which attain temperatures in the range from tens of eV to tens of thousands of eV. In typical magnetic confinement devices (e.g., tokamaks, stellarators, reversed field pinches, mirror devices) an externally produced 1-10 Tesla magnetic field of carefully chosen geometry is imposed on the plasma. Magnetic confinement devices generally have densities in the range $10^{19} - 10^{21}$ $m^{-3}$. Plasmas used in inertial fusion are much denser; the goal is to attain for a brief instant densities one or two orders of magnitude larger than solid density ($\sim 10^{27}$ $m^{-3}$)[9].

### 1.6.3 Space Plasma

The parameters of these plasmas cover an enormous range. For example the density of space plasmas vary from $10^6$ $m^{-3}$ in interstellar space, to $10^{20}$ $m^{-3}$ in the solar atmosphere. Most of the astrophysical plasmas that have been investigated have temperatures in the range of 1-100 eV and these plasmas are usually fully ionized[9]

**Fig 1.1: Lagoon Nebula is a large , low density cloud of ionized gas (plasma)**[10]

## 1.7 Types of plasma

### 1.7.1 Hot plasma (Thermal plasma)

A hot plasma is one which approaches a state of local thermodynamic equilibrium (LTE). In a high-pressure gas discharge the collision between electrons and gas molecules occurs frequently. This causes thermal equilibrium between the electrons and gas molecules. We have $T_e \simeq T_g$ , where $T_e$ and $T_g$ are the temperatures of the electrons and gas molecules, respectively. We call this type of plasma a "hot plasma'. A hot plasma is also called a thermal plasma. Such plasmas can be produced by atmospheric arcs, sparks and flames. A hot plasma can be found also in the Sun and other stars[11].

### 1.7.2 Cold plasma (Non-thermal plasma)

Plasma is produced by the provision of heat to a gas. Hence, we might think that plasma is always hot in nature. However, not every plasma is hot. Before proceeding further, let us try to refresh our knowledge of temperature and heat. It is a common misconception that higher temperature should always mean a lot of heat. When defining the hotness or coldness of a given substance, one must not only consider its actual temperature but also its heat capacity. For example: the temperature of the electrons inside the fluorescent lamp in your room is 20,000 K, although the lamp does not feel hot when you touch it. This is because the number of high-temperature electrons inside your lamp is very low compared to the air at room temperature. Thus total heat transfer to the wall of the lamp by these electrons striking the wall is not sufficiently high. Hence, the heat capacity of the plasma in the fluorescent lamp is low, keeping the wall of the lamp at room temperature. Let us take another example: You might have experienced accidentally dropping the ash of a cigarette on your hand. Even though the temperature of the ash is very high, you were probably not immediately burned. This is because the total amount of heat involved is very low. Cold plasma (or non-equilibrium plasma) is the plasma where the temperature of the individual constituents are different from each other. Electrons are at higher temperature (more than 10,000K) and neutral atoms are at room temperature. However, the density of the electrons in the plasma is very low compared to the density of the neutral atoms. In the laboratory, cold plasmas are generally produced by the provision of electrical energy to different inert gases. This can be done at room temperature and at atmospheric pressure. This means that weThere are two very fascinating things about cold plasma. First, cold plasma is a source of high-temperature electrons at ambient conditions (room temperature & pressure). Second, cold plasma - when interacting with an open or controlled environment, produces many reactive species. Those reactive species can be used for many chemical reactions in different fields of science. avoid all the hassles of big costly instruments, making cold plasma technology affordable. There are two very fascinating things about cold plasma. First, cold plasma is a source of high-temperature electrons at ambient conditions (room temperature & pressure). Second, cold plasma - when interacting with an open or controlled environment, produces many reactive species. Those reactive species can be used for many chemical reactions in different fields of science. Such a plasma composed of the same number of electrons and ions. In low pressure gas discharge, the collision rate between electrons and gas molecules is not frequent enough for non-thermal equilibrium to exist between the energy of the electrons and the gas molecules. So, the high-energy particles are mostly composed of electrons while the energy of the gas molecules is around room temperature. We have $T_e >> T_i >> T_g$ where $T_e$, $T_i$ and $T_g$ are the temperatures of the electron, ion and gas molecules, respectively. This type of plasma is called a "cold plasma". In cold plasma, the degree of ionization is below $10^{-4}$ [11].

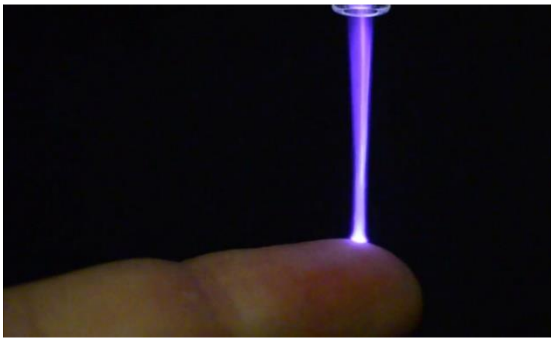

**Fig 1.2: The cold plasma**[12]**.**

## 1.8 Laser-Plasma Interactions

When a high-power laser beam interacts with a plasma, several processes can occur:

1. **Self-focusing**: The intense electric field of the laser beam can cause the plasma to become nonlinear, leading to self-focusing of the laser beam within the plasma.
2. **Plasma wave generation**: The intense laser beam can drive plasma waves, such as Langmuir waves or electron plasma waves, through a process known as stimulated Raman or Brillouin scattering. These waves can carry energy and momentum through the plasma.
3. **Particle acceleration**: The interaction between the laser and the plasma can accelerate charged particles, such as electrons or ions, to very high energies. This acceleration can occur through mechanisms like laser wakefield acceleration or direct laser acceleration.
4. **Plasma heating**: The laser beam can deposit energy into the plasma, heating it and causing it to expand or undergo various instabilities.

5. **Nonlinear optics**: The intense electric field of the laser beam can induce nonlinear optical effects within the plasma, leading to phenomena like harmonic generation or frequency mixing.

The propagation of intense laser pulse in plasma is relevant for a variety of applications, such as laser fusion schemes, laser–plasma accelerators, harmonic generation, X-ray sources, and terahertz (THz) radiation generation. Owing to the myriad scientific and technological applications of THz radiation, it has attracted much attention presently.[13].

Optimal use of high power lasers for the numerous applications motivate an ongoing strong

effort to improve the understanding of laser matter interactions. These interactions are remarkably rich, ranging from classical inverse bremmsstrahlung absorption and many laser-driven plasma instabilities, to strongly relativistic plasma phenomena. The interaction pro- cesses are coupled with energy transport phenomena, which are very complex for intense heat fluxes. Laser plasma interactions are proving to be a fascinating and challenging test bed for nonlinear physics. In laser-plasma interaction, ultrahigh intensities produce a wealth of nonlinear phenomena, in- cluding strong wakefield excitation, self-focusing, and wave-wave interactions such as stimulated Raman scattering. Laser driven plasma wakefield accelerators are about one thousand times more compact that conventional accelerators based on microwave cavities, which are usually limited to about 20 MV/m for superconducting cavities and about 100 MV/m for room temperature devices. To achieve very high energies long and expensive multi-staged accelerators are required. Their high cost is due to the numerous microwave power sources required, the highly engineered accelerator systems and the huge shielding infrastructures needed to house them. Furthermore, the duration of electron bunches from conventional accelerators are restricted to between 100 fs and several tens of picoseconds. Achieving shorter durations and high peak currents requires bunch compressors, which adds to the complexity and cost of state-of-the art accelerators. Apart from the well known use of accelerators to study the sub-atomic structure of matter, such as searching for the Higgs Boson, high energy accelerators are central components of light sources. Light sources are some of the most useful tools available to scientists and technologists for mapping out the molecular and solid state structure of matter. They have become essential tools for developing drugs and new materials, and are powerful sources for imaging matter on all length scales, offering unique windows into biological function. Light sources, such as synchrotrons, which are often called third generation light sources, have become ubiquitous brilliant sources of incoherent radiation covering an extremely broad spectral range, from terahertz frequencies (millimeter wavelengths) to hard X-rays. Free-electron lasers, which are coherent sources based on high peak current, high brightness accelerators, and undulators, are being developed as fourth generation light sources. FELs produce brilliant ultra-short pulses of coherent radiation that is tuneable over a very wide spectral range, similar in extent to synchrotrons but restricted to photon energies of the order of several keV because of the extreme demands on the electron beam quality and peak current required to develop micro- bunching on an ngstrom wavelength. Synchrotrons require high repetition rate electron bunches with high average currents and energies in the range of 0.5 GeV to more than 10 GeV, whereas FELs usually require lower energy, high peak current electron beams with durations less than 100 fs to achieve high peak currents with modest totsl charge. Infrared FELs, on the other hand, are based on 10’s MeV electron beams and are usually low gain oscillators consisting of undulators contained in an optical cavity to allow trapped radiation to build up over many repetitive micro- pulses. However, VUV to X-ray FELs are usually high gain single-pass amplifiers because of the lack of suitable cavity mirrors for oscillators in this wavelength region[2]. Measuring wakefield amplitudes in a channel guided LPA(Laser Plasma Acceleration) is difficult due to the complex dynamics of the laser pulse. Techniques such as frequency-domain interferometry and frequency-domain holography can measure wakefield structures. However, such experiments require probe pulses and multiple shots to characterize wakefields observed by e-beams for many Rayleigh lengths. Optical spectrum shifts of a driving laser have also been used as wakefield diagnostics. The spectral redshifts are directly related to laser energy depletion in the plasma. Energy transferred from the laser to the plasma is converted to energy in longitudinal and transverse wakefields. Murphy et al. detected a large amplitude wakefield through “photon acceleration”. This technique requires the laser pulse to be longer than optimal for wake excitation. For the regime discussed in this section, the laser pulse was too short to experience this effect. More recently, optical spectra have been used to measure excited wakefields in gas-filled capillary tubes. This analysis reported good agreement between experiment and theory for the case of wake excitation in a linear regime where the laser pulse was guided in the channel without significant transverse evolution. In this analysis, spectral shifts are studied to diagnose wakefields in a plasma channel with strong laser evolution resulting in linear and nonlinear wakes. Without transverse laser evolution, the ratio of energy going into the longitudinal and transverse fields is nearly constant. However in many experiments, the transverse evolution of the laser can be significant, resulting in a varying partition of laser energy into the longitudinal and transverse fields as a function of propagation distance. Therefore, understanding both the efficiency of the total laser energy transfer into the plasma, and the energy partition between longitudinal and transverse fields are important for estimating the accelerating fields in an LPA. Our analysis identifies some of the critical experimental parameters that influence the efficiency of the laser energy transfer into the plasma. Specifically, the influence of input laser energy, plasma density, temporal and spatial laser pulse shape, and laser coupling condition defined by laser focus position and longitudinal plasma density profile are studied experimentally and numerically. In addition to the expected increase in the energy transfer efficiency with laser intensity and plasma density, the efficiency is found to be particularly sensitive to the temporal pulse shape and the laser coupling condition[14].

The radiation emitted by a charged particle during the collision with another particle is customarily called bremsstrahlung (in German 'braking radiation') because it was first detected when high-energy electrons were stopped in a thick metallic target. Inverse bremsstrahlung is the process in which an electron absorbs a photon while colliding with an ion or with another electron. A rigorous calculation of the inverse bremsstrahlung absorption can be made by using the kinetic theory (e.g. the Vlasov equation) to take into account the distribution function of the electrons and the positions of the ions. In this case the absorption coefficient depends on the correlation function of the ions.

Here we consider a simple model where the plasma is infinite and homogeneous, the ions are infinitely heavy (i.e. their motion is neglected) and no static magnetic or electric fields interfere. Since the electromagnetic waves have a phase velocity much higher than the thermal velocity of the electrons it is justifiable to neglect their thermal motion. Thus the equation of motion for the electrons is

$$d\boldsymbol{v}/dt=(-e\mathbf{E}/m_e)-(\boldsymbol{v}/\boldsymbol{\tau}_c) \quad (5)$$

where **-e**, $\boldsymbol{m_e}$ and $\boldsymbol{v}$ are the electron charge, mass and velocity, respectively, **E** is the electric field and $\boldsymbol{\tau}_c$ is the effective time between electron–ion collisions (we neglect the electron-electron collisions).

## 1.9 Applications of Laser-Plasma Interactions

### 1.9.1 Particle Accelerators

The recent advances in developing lasers with more energy, power, and brightness have opened up new possibilities for exciting applications. The electric fields that can be achieved with intense lasers have paved the way to a new technology for particle accelerators. For nearly 100 years, acceleration of charged particles using electromagnetic fields has been carried out. The goal of this field has been to continually achieve higher energies to examine, in finer detail, the basic constituents of matter. Great progress has been made; however, due to limitations on the maximum electric fields that can be obtained by conventional techniques larger and larger accelerator systems have become necessary to achieve higher energies. The cost of such systems is so huge that multinational collaboration and construction over many years is required. One method to achieve higher accelerating fields is using laser–electron and laser–plasma interactions. In recent years, rapid progress in this type of acceleration has been brought about by the development of ultrashort high-power lasers via the chirped pulse amplification method. This technique allows generation of high irradiance lasers of ultrashort duration[15].

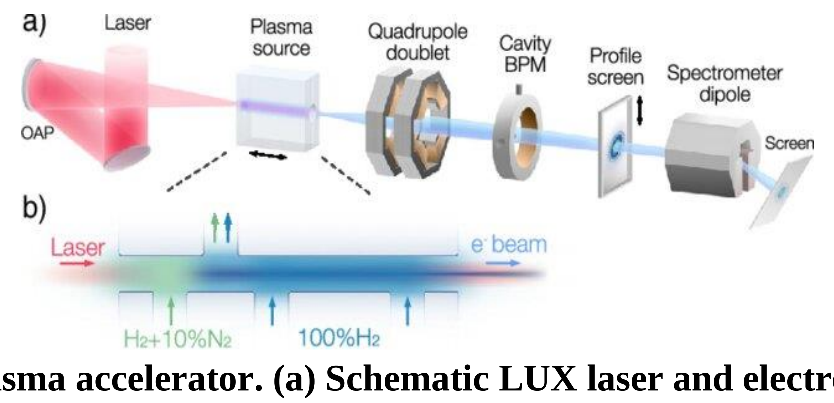


**Fig 1.3: Laser-plasma accelerator. (a) Schematic LUX laser and electron beam line.**

**(b) Structured plasma source supplied with $H_2$ and doped with 10% $N_2$ in the front for controlled injection of electron bunches into the laser-driven plasma wave.(Image cridit: Manuel Kirchen)**[16]**.**

### 1.9.2 X-Ray Sources

The applications of these sources are used with high-power, short-pulse durations and small dimensions obtained in laser– plasma interactions. Intense electromagnetic radiations emanate from laser-produced plasma (LPP). Soon after the invention of lasers, the possibility of LPP as a new radiation source was investigated. In particular, new laser technologies such as oscillation with a Q-switch, mode locking, chirped pulse amplification to laser systems, and shorter duration and higher power laser pulses became available. As a consequence, one can generate intense radiation pulses extending from terahertz wave (∼100 μm in wavelength), visible light, extreme ultraviolet light (EUV, ∼10 nm), and x-rays (0.1–1 nm) to γ-rays (<<0.1nm). Emanation of dominant radiations is controlled by optimizing laser-irradiation conditions and target materials. For example, conversion efficiency, defined by the ratio of the x-ray radiation emitted in whole space to laser energy onto the target, can be as high as 80% when a target consisting of high-Z materials such as gold is irradiated with frequency- tripled Nd:glass laser light at $10^{13}$ W/cm$^2$. Such a high conversion efficiency enables us to drive a fusion pellet to attain high fusion gain. Intense radiation pulse is very useful to observe the dynamics of rapidly moving hot-dense materials such as laser-driven fusion pellets, live organisms, transient phenomena of shock-compressed crystalline matter, and objects of nondestructive inspections. LPP radiation is a compact pulse source, thus it has been extended to a wide variety of industrial and scientific applications[15].

### 1.9.3 Nuclear and Particle Physics with Ultraintense Lasers

Ultrahigh power lasers generate high fluxes of energetic photons, electrons, protons, and ions that are used for the study of applications of nuclear and elementary particle physics. With the advent of ultraintense lasers, a new area was opened for nuclear and high-energy physics research. A wide variety of phenomena, such as heavy ion-induced nuclear reactions, fusion evaporation, isotope production for positron emission tomography (PET), or photontransmutation of long-lived nuclear waste, have been studied in recent years mainly using 100 TW laser intensities. These nuclear phenomena result from the efficient acceleration processes taking place in intense laser– plasma interaction experiments, which lead to the generation of fast electron and ion beams, and the subsequent emission of high-energy photons and neutron beams. Intense laser–plasma interactions can therefore provide a new environment for nuclear physics research, but no new nuclear processes have been considered so far[15].

### 1.9.4 Nanoparticles Induced by Femtosecond Lasers

A particle with a dimension larger than about 1 nm and smaller than 100 nm is arbitrarily defined as a nanoparticle (NP). Sometimes particles less than 10 nm are referred to as NPs and the larger particles up to about 1 μm are called mesoparticles, where the material's properties are closer to those in its bulk. NPs are of great interest because of the physics associated with them, namely, NPs possess a large surface-to-volume ratio and they are macroscopic objects described by quantum physics. NPs can exhibit very different physical and chemical properties in comparison to macroscale particles. Opaque matter (such as copper) becomes transparent to visible light, insulators transform into conductors, inert materials (like platinum or gold) behave as catalysts, melting temperature of material changes significantly, etc. The fascinating nanotechnology follows from these unique quantum physics and the large surface-to-volume ratio of the nanosystem. These NPs may also prove very important and useful to many industrial and biological applications. Thus, the synthesis and study of NPs of various elements and compounds is of great interest both in technological applications and for fundamental researc[15].

## 1.10 Aim of Research

**1**. Generating cold plasma using argon gas.

**2**. Study the laser plasma interaction using an intense laser.

**3**. Study the laser propulsion engine, work under the process of laser-plasma interaction with intense laser.

# Chapter Two

# Experimental Part

## 2.1 Generating of Plasma

One particularly notable and widely employed technique is plasma jet technique, which, due to its simplicity, holds significant promise for enhancing our understanding of complex physical processes. Plasma jet technology is not only confined to laboratory settings but has also found practical applications in medical contexts, particularly in the field of sterilization. The unique properties of plasma, including its ability to generate reactive species, make it an effective tool for inhibiting bacteria and ensuring sterilization. This dual application underscores the multifaceted nature of plasma jet technology, illustrating its potential impact on both scientific research and practical, real-world applications. Plasma jet technology has found applications in medical fields and sterilization processes, marking it as a useful tool with multifaceted implications. The spectroscopic analysis serves as a powerful tool offering a nuanced perspective into the behavior and composition of plasma, providing invaluable insights into the interactions among its constituent species. This approach enables researchers to unravel the intricacies of interactions between atoms and ions, yielding crucial information regarding their energies, densities, and elemental compositions. Optical emission spectroscopy (OES) stands out among the array of spectroscopic methods frequently employed to analyze plasma characteristics. In OES, electromagnetic radiation emitted by excited atoms and ions in the plasma is detected and analyzed. This emission results from transitions between energy levels of these species, delivering valuable information about their populations, energy distributions, and temperatures. OES proves instrumental in identifying ratios of ions and neutrals present in the plasma, thereby offering insights into the composition and ionization state of the plasma species. The application of spectroscopic study allows scientists to discern variations in plasma behavior, prompting investigations into elemental distribution, species concentration, and energy distributions. This comprehensive examination advance our understanding of plasma dynamics, thereby contributing to the optimization of plasma-based technologies in various scientific and industrial domains[3]. In this experiment, the effect of laser plasma on plasma and acceleration has been proven. A positive voltage was placed on the detector to measure the electron current. In this experiment, the detector was installed at a fixed distance from the plasma outlet in order to measure the lowest possible electron current for the plasma. After that, laser pulses were run to see its effect on the plasma. The laser and plasma were aligned in one line, as shown in Figure 2.1.

## 2.2 Experimental Setup

The experimental configuration, as depicted in (figure 2.1), comprises a plasma jet system featuring a tube housing externally electric electrodes. The tube facilitates the flow of gas, which undergoes ionization upon exposure to the electric current generated between the electrodes. In this setup, a positive voltage was connected to the detector and a micrometer to read the electron current($I_e$). Plasma is ignited within the nozzle/tube and subsequently directed outside the target area for treatment via gas flow. The plasma jet employs argon gas. A high-voltage power source were used to supply gas ionization. The system is alinged so that the laser is in line with the plasma.

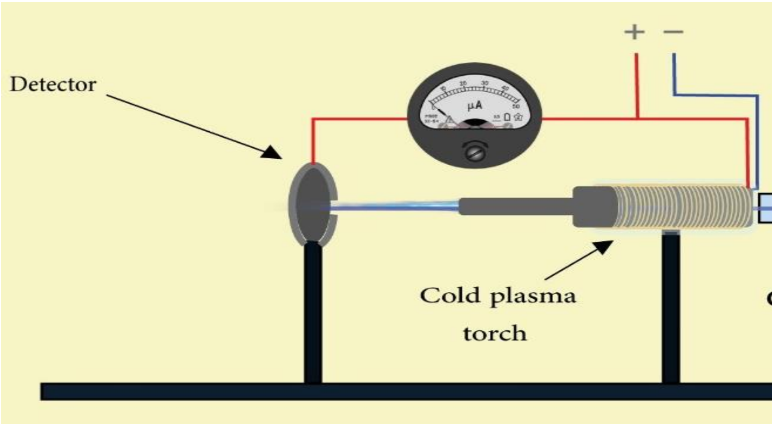


**Fig 2.1: The plama jet system scheme.**

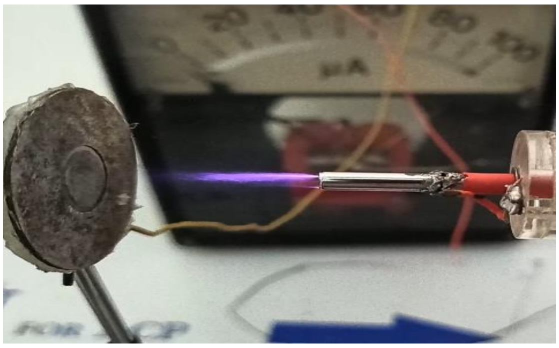

**Fig 2.2: A photograph for the plasma jet system**

The plasma used in this experiment is Ar plasma. Ar Plasma is one of the most common types of plasma used for cleaning due to its low cost, ability to prevent oxidation, and wide availability. The spectra emitted from the plasma generated from atmospheric plasma jet technology using Ar gas lies within the wavelength range from approximately 300 to 450 nm, which belongs to the molecular spectrum of nitrogen, which is the largest component of atmospheric air[3]. A violet/blue 500 mW laser used with a wavelength of 405nm, which is within the wavelength range of the plasma. Matching the wavelength of the laser spectrum with the wavelength of the plasma is very important, as to produce laser-plasma acceleration, the phenomenon of resonance must occur between the wavelengths of the laser and the plasma. The laser is aligned with the system so that it is in the same direction as the plasma flow to provide propulsion.


**Fig 2.3: The laser used of 500 mW output and 405 nm wavelength.**

# Chapter Three

# Results and Discussion

## 3.1 Results

The change in electrons current with the change in time readings were taken using manually laser pulses. The results in table 2.1 shows an obvious effect of laser on the current.

**(Table 3.1) Current Vs Time**

| t (sec) | I $\mu$ A |
|---|---|
| 0 | 0.5 |
| 2.17 | 1 |
| 2.54 | 0.5 |
| 3.01 | 1.1 |
| 3.52 | 0.5 |
| 4.14 | 1 |
| 5.72 | 0.5 |

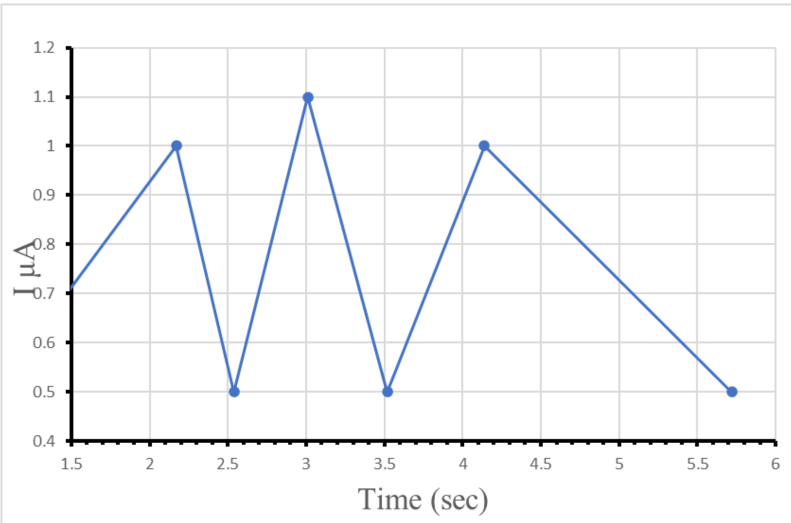


**Fig 3.1: The electrons current vs time between pulses**

## 3.2 Discussion

Increasing the value of the current with the pulses means increasing the speed of the electrons that travel the distance (x) between the plsma source and the detector. Changing the distance leads to changing the current values as well. As the distance decreases, the value of the current increases, but it was found that at a certain distance between the detector and the plasma source, the direct discharge of charges occurs due to the presence of the positive electrode on the detector. Therefore, if values for the current are taken in this case, it will represent the discharge current and not the plasma current.


(a) (b)

**Fig 3.2: Current increasing with laser pulses, (a) shows the electron current when laser intensity equals to zero, there is no change in current, where the current here equals to 0.5 µA. (b) shows the current with a laser pulse of intensity of 500 mw, the current has increased to 1 µA.**

When a laser pulse interacts with a charged particle, it accelerates the particle based on the Lorentz equation (ignoring radiation reaction effects)[15].

$$\frac{d\boldsymbol{p}}{dt} = q(\boldsymbol{E} + \boldsymbol{\beta} \times \mathbf{B})$$

**Where** $p = \boldsymbol{\gamma}.m.v$ is the momentum, $\boldsymbol{m}$ is the electron mass, $\boldsymbol{q}$ is the charge, ( $\boldsymbol{E}$,$\boldsymbol{B}$) are the electromagnetic fields, and $\boldsymbol{\beta} = \boldsymbol{v}/c$, and $\gamma = 1/\sqrt{1 - \boldsymbol{\beta}^2}$ are the Lorentz factors with $\boldsymbol{v}$ being the velocity.

### 3.3 Conclusion and Suggestions

Although the effect of laser with low intensity with electrons was weak, so that the amount of current increase is 0.5 mA, but it is conclusive evidence that the laser affects the plasma. From conducting this experiment, we conclude that the laser can be used to accelerate particles, as the increase in current after turning on the laser indicates that the speed of the electrons increased, so they began to cover the same distance faster and in a shorter time. Using lasers with a shorter pulse time and higher intensity will certainly lead to stronger currents. The phenomenon of particle acceleration by laser can also be used to create a proton propulsion engine, it is a jet engine that works on the basis of the phenomenon of propelling protons (heavy compared to electrons) with intense laser pulses. Protons have a greater mass than electrons, and therefore they have a much higher momentum than electrons, and this leads to producing a greater momentum than what an electronic engine produces.

For future goals, it is better to use a laser with a higher intensity than the one used in this experiment. Also, the parameters of the entire system must be calculated and the gas flow rate of gas must be included because it has been shown that it affects the plasma spectrum and thus affects the phenomenon of resonance between the laser and plasma spectrum. Using a better detector than the user may lead to better results, the detector used in the experiment was manufactured manually.

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