Intense infrared lasers and laboratory astrophysics

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Abstract. Electrons accelerate due to the huge electric field of the laser itself, and so they can generate very particular plasmas because the ionization process occurs in a few femtosecond, or even in a fraction of a femtosecond. Lasers can be focused now to intensities beyond $10^{22} \text{W/cm}^2$ and there are projects to arrive up to $10^{26} \text{W/cm}^2$. Electric fields of the laser arrive now to $10^{14} \text{V/cm}$ and magnetic fields reach the Megatesla. This is a monster density of electromagnetic energy, so that we are close to obtain light denser than matter. In this respect it is very convenient to observe that the well known Einstein’s energy - mass equation, $E = mc^2$, can be rewritten for laser light $I = c^3$, $I$ being the laser intensity and $\rho$ the equivalent density. There are several PW lasers around the world, in operation or in construction, and one of them is going to be at Salamanca’s CLPU.

1. Introduction

Extreme plasma physics needs extreme tools and present day lasers can be considered as such extreme tool. The necessity of extreme lasers was clear soon after the discovery of the lasers -if not before-. By mid-eighties, a group of researches at the Laser Laboratory at the University of Rochester (Rochester, NY), lead by Gerard Mourou, discovered a very clever trick to boost the laser peak power. This was the launching of the ultraintense laser technology. This new technique was soon known as Chirped Pulse Amplification, since it relies in the introduction of chirping in the broadband laser pulses before amplification [1]. Chirped Pulse Amplification is now a well developed technology [2]. It has allowed the most intense lasers ever dreamed of [3].

Now with those lasers monster pressures, huge accelerations, and electric and magnetic field without equivalent on Earth. Moreover we try to justify that those lasers differ very much of the standard concept of a laser. First, they have nothing to do with monochromatic light. Those lasers are short time (femtosecond) and thus they are broadband. Second, they are not really light beams, but light bullets. A 30 femtosecond pulse, for example corresponds -for 800 nanometer wavelength- to 10 microns. So when focused, this laser delivers something closer to a light bullet than to a light beam [4].

2. Present status of light-mater interaction phenomenology.

It is important to concentrate the peak power over a very small focal spot, because most of the phenomenology depends on the electric field at focus [5]. The phenomenology of the interaction of such lasers with atoms, molecules and nuclei is very rich and surprising. Our understanding of the light-mater phenomenology has been very rapidly changing over the last decades. We review now the most important milestones.
Below $10^8$ W/cm$^2$, approximately, the phenomenology is the standard Einstein photoelectric effect, in the sense that the photon is so short in energy to ionize. However, from $10^{10}$ W/cm$^2$, there are so many photons involved in the ionization that several of them can bring the necessary energy for releasing the electron, leading to multiphoton ionization. One of the main rules of Einstein's photoelectric effect, the need of a photon more energetic than the binding energy of the electron now fails and ionization can occur with the absorption of a number of photons, not necessarily the minimum number of photons to arrive to the continuum, but more of them (in that case, the effect is known as above threshold ionization). This is the prevailing phenomenology until the electric field itself begins to play a role and suppress the Coulomb barrier that bounds the electron to the atomic nucleus. Beyond $10^{16}$ W/cm$^2$, electrons are simply released over the ionization barrier by something similar to the DC Stark effect. From this point on, ionization is simply due to the electric field strength, and dynamics is completely different from the multiphoton regime.

To have an idea of the strength of the field it is worth to remember the definition of the atomic unit of intensity. Atomic units are determined by $m = e = \hbar = 1$, $\hbar$, being the Planck constant, $m$ the electron mass, and $e$ the absolute value of the electron charge. In atomic units the speed of light is $c = 137$. The atomic unit of intensity is $3.57 \times 10^{16}$ W/cm$^2$, an intensity that has been achieved for more than two decades. This intensity of the laser field corresponds to an electric field amplitude of $5.14 \times 10^9$ V/cm. Just by the definition of atomic unit, the atomic unit of electric field this is the field experienced at a distance equal to one atomic unit (one Bohr radius) of a proton, i.e. is the electric field that an electron in the ground state of the hydrogen atom feels. This means that beyond the atomic unit of intensity electrons-laser coupling is stronger that electron-nucleus coupling. So beyond atomic unit of intensity electrons are suddenly released from atoms by over the barrier ionization and move freely driven by the laser field. Thus generating instantaneously -in a few femtoseconds- a strongly driven plasma.

3. Laser acceleration.

As intensity increases, atoms have no meaning, and we must consider just a plasma of electrons and positive ions. Not only valence electrons are ionized, but inner shells can arrive to the barrier suppression regime. Two orders of magnitude more and the magnetic of the laser field begins to be relevant for the dynamics of the driven electrons. For the Ti:Sapphire wavelength (800 nanometer) ionized electrons travel at relativistic speeds [5] at intensities beyond $10^{18}$ W/cm$^2$. A relevant feature of the strong laser field driven electron is that it starts at rest, accelerates to a large speed in a one or a few femtoseconds. The acceleration is extremely high and so radiation effects may become important.

There are also some laboratories working in laser acceleration with far infrared lasers, as the 10 micrometers CO$_2$ laser [6]. But such long wavelengths imply other unavoidable fundamental problems: the focal spot minimum size is governed by diffraction and so is proportional to the wavelength. On the other side of the spectra, ultraviolet lasers have fields oscillating too fast for a convenient acceleration in one cycle. As a result, near infrared seems nowadays to be the best option for acceleration.

As we jump in the intensity ladder to values of the order of $10^{21}$ W/cm$^2$, protons are also relativistically driven. As protons have a larger mass they need a higher intensity to become relativistic. As intensity increases other ions are also relativistically driven. In all cases, obviously the important parameter is the charge/mass relation.

4. Relativistic plasmas.

In the same way a laser accelerates a free particle, it accelerates a collection of charged particles a plasma. When a laser is focused at those relativistic intensities on a target, it generates a plasma of relativistic electrons and if the intensity is large enough- also of relativistic ions.
The plasma appears in a few femtoseconds and thermatization is at those time scales a slow process. Released electrons moving close to the light speed have no time to feel their electrostatic repulsion and keep plasma densities close to solid densities for a few femtoseconds thus generating huge electrostatic fields that in turn can help in the accelerations process. As a consequence, new plasma effects such as wakefield acceleration for tens of femtoseconds pulses- and bubble accelerations for few femtoseconds pulses- are now under study. We must also indicate that it is extremely difficult to measure the intensity at such frontier region. We can assume that a petawatt laser with a good wavefront quality can arrive to $10^{23} \text{W/cm}^2$, without great difficulty. Observe that a petawatt ($10^{15}$ watt) focused into a spot of one squared micrometer corresponds to that intensity. However many times the best wavefront quality is achieved with a somewhat not so extreme intensity, and the reported records, close to $10^{23} \text{W/cm}^2$, correspond to lasers of multi-hundred terawatt power [7]. This $10^{23} \text{W/cm}^2$ number can be considered as today’s world record of intensity. It is feasible with titanium:sapphire lasers (800 nanometer) and about 30 femtoseconds pulse duration. This intensity corresponds to $8.6 \times 10^{12} \text{V/cm}$, for the electric field amplitude, and a magnetic field amplitude of $2.8 \times 10^6 \text{Tesla}$, which are extraordinary numbers. Of course, those fields are oscillating fields with a 2.6 femtosecond period, so those maximum amplitudes last one femtosecond (imagine if those values were with static fields). But at those extreme fields even a fraction of a femtosecond is enough to induce extreme effects.

5. Density equivalent

To convince the reader that a laser pulse well focused correspond to a monster concentration of energy we propose the following analogy. A 30 femtosecond laser pulse is a veil of light just 10 microns thick moving at the speed of light. If this is focused to a spot size of, for example, 1 squared micron, we have all the pulse energy concentrated on a volume of 10 cubic microns. A very small volume. But this is the key feature of lasers, we are now able to concentrate energy in a never before dreamed way. More precisely if $\rho$ is the mass density (mass divided by volume) then the energy density is $\rho c^2$ for mass. In the case of a laser focused to a given intensity $I$, it is straightforward to show that the energy density is given by $I/c$. So we can consider that each intensity corresponds to a mass density, understanding that this is just an analogy to understand the meaning of such extreme fields. The density to intensity relation is therefore $I = \rho c^3$. This relation is very basic and illuminating. Always has been considered that matter is a huge concentration of energy, and when just a tiny fraction of that energy can be released (as in nuclear reactions) it has important consequences. Light is energy by itself, since it is electromagnetic energy. Einstein mass energy relation corresponds approximately to $9 \times 10^{13} \text{Joule/gram}$. This is a very important quantity of energy because we consider one cubic centimeter of water, for example. If instead of this volume, we would consider just one cubic micrometer of water, then this energy is just 90 J, an important energy but maybe soon achievable with a laser.

What we learn from Table 1 is that present day lasers are close to water density equivalent. According to the evolution of the technology it is expected to arrive in a couple of years to intensities of the order of $10^{25}$ to $10^{26} \text{W/cm}^2$. Although this is just a didactic analogy, it shows that state of the art CPA lasers are a fabulous tool that provides a huge concentration of electromagnetic energy, relevant for many applications and without precedent on Earth.

6. Is there a limit in the laser intensity?

A laser beam is a collection of photons, since photons are bosons then it can be possible to place infinite photons in the same state and thus there are no limits for the intensity of any laser. This seemed just an academic question for many decades, but maybe we are close to
Table 1. Some typical values of the density of mass and their translation into energy density according to the Einstein energy-mass conversion equation. At the right column we can see their intensity equivalent.

| Density | Energy Density | Intensity |
|---------|----------------|-----------|
| air     | 0.001 gr/cm³   | 0.09 J/μm³ | 2.69 × 10²¹ W/cm² |
| today’s-lasers | 0.037 | 3.40 | 10²³ W/cm² |
| water   | 1              | 90        | 2.69 × 10²⁴ W/cm² |
| sun-core| 100            | 9000      | 2.69 × 10²⁶ W/cm² |
| Schwinger-limit | 85733 | 3 × 10⁶ | 2.3 × 10²⁹ W/cm² |
| withe-dwarf | 1000000 | 9 × 10⁷ | 2.69 × 10³⁰ W/cm² |

experimentally explore this limit. Quantum electrodynamics, QED, is the theory that describes the interaction of electromagnetic fields with charged particles, as well as the creation of pairs of particles in the presence of such fields, and related processes. From the early times of QED it was clear the existence of a critical field that can not exceed because of the spontaneous creation of electro-positron pairs. This critical field is now known as the Schwinger limit, since it was clearly identified and studied by this author [8] although it appeared in other previous works. The Schwinger critical field is 1.3 × 10¹⁶ V/cm, that corresponds to a laser intensity equal to 2.3 × 10²⁹ W/cm² and to a magnetic field of 4.4 × 10⁹ Tesla.

At early QED times the Schwinger limit was just academic, since it was too far from experimental possible sources. Now this limit is still far but not too far and a lot of recent research activity is trying to understand much more precisely the Schwinger limit [9], and its onset. Close to the critical field, electron-positron pairs can appear from vacuum and vacuum thus becomes unstable since the number of pairs is so large that they take a significant fraction of the laser pulse energy.

Since we are entering the region where light can generate pairs from vacuum, a lot of new questions are appearing those days. Moreover, two co-propagating high energy-photons cannot generate a particle pair since momentum-energy conservation has to be violated. In the case of the laser this is true, but now one million photons combine to give a pair, and momentum-energy conservation can be addressed in different practical ways: - If the laser beam is divided into two parts that collide head on. In that case pair creation process is maximized. This is closer to standard photon-photon collision with the peculiarity that the centre of mass energy of the photon-photon collision is a few eV, so millions of photons must act collectively to generate a pair. A number of studies are now under progress to design experiments of photon-photon scattering in vacuum [10].

- A focused beam implies a convergent wavefront and thus all photon momenta are not strictly parallel. So pairs can also appear in a relatively efficient way.

- A last strategy to check the QED limit is to use just a collimated beam and to introduce a counter-propagating accelerated electron. The Lorentz boost from the lab frame to the approaching electron frame enhances the efficiency of pair production [11].

There are thus many strategies under progress to analyse the decay of the quantum vacuum. Also there are many uncertainties, that now are very relevant because they can imply design of very expensive near future experiments. Two of the most relevant are:

- Are there charged particles with a mass smaller than the electron mass? If so, since the Schwinger critical field scales with mass, pairs of these hypothetical particles would appear before electron-positron pairs.

- Pair creation process is a tunnelling process and tunnelling dynamics still is not very
understood in many aspects. In this case, the generated particles appear inside a huge electromagnetic field, and therefore they suffer an intense acceleration just at the moment they are created. Most of the theories indicate that the pair is first generated and once it is real both individual particles are accelerated. However it could also be possible that the energy for the pair creation is not just the rest energy but the energy they need to gain to be inside the field (the so called ponderomotive energy). In that case the Schwinger limit will be shifted to higher intensities.

Therefore, close to the Schwinger limit there should be a fundamental limit of the intensity attainable with a high power laser. It is not clear if this limit will occur before or after the Schwinger critical field, but it is clear that something will happen and that high intensity studies are necessary. There are some efforts as ELI [12] to build in the future hundred Petawatt lasers that will allow experimental work on this. At $10^{26} \text{ W/cm}^2$, if not before, most theories indicate that vacuum is non-linear and that virtual pair production will have some effects. Maybe such intense lasers will propagate in vacuum at a speed lower that $c$?

Having a conceptual upper limit for laser intensity, even when the laser is just loosely focused, is an interesting basic physical problem that needs a lot of future theoretical research. But such necessity of new modeling does not end with the existence of an upper limit. It is clear that pairs will appear and that those pairs will be violently accelerated. There are some clues that indicate that the acceleration of electrons in such extreme lasers can be relevant for general relativity and it is expected that such electrons self-generated, or injected- close to the Schwinger limit will radiate in a similar way as in the proximity of a black hole. This kind of radiation, the so-called Unruh radiation is now subject of intensive study, and fundamental experiments to measure it are under design [13].

7. Applications in astrophysics

Probably the existence of such fundamental questions is enough to trigger new research in ultraintense lasers and to justify the important economical efforts necessary to build them in the next decade. Moreover there are a lot of applications of such future lasers. Among them, the most relevant application is particle acceleration. Lasers are starting to be considered as the new paradigm for particle acceleration because a laser can accelerate a particle to GeV or maybe TeV energies in a few millimeters distance.

Laser accelerated plasmas are a new experimental field that can be relevant for several applications including the modeling of astrophysical phenomena. There are a number of publications devoted to the laboratory model of astrophysical processes [14]. Among them, there is a number of nonlinear plasma effects that can be clarified with lasers. There are also some problems on relativistic astrophysics, as cosmic ray acceleration, and as the interaction of electromagnetic waves with relativistic plasmas that can be clarified with the use of ultraintense lasers. Also relativistic solitons and vortices and collisionless shock waves can be studied with lasers.

Being a bit more optimistic, future lasers can generate so violent accelerations that can propose new specific tests to general relativity. The experimental search of Unruh radiation in laser accelerated plasmas can help to the validation of some models of black holes.

Anyhow, extreme laser modeling of astrophysical plasmas will take some time, probably decades to be mature. In between lasers are becoming relevant to study nucleogenesis and fusion reactions similar to the Sun’s interior, and the experimentation with dense plasmas is advancing very quickly.

8. Conclusions.
Ultraintense lasers are evolving as a conceptually new tool to explore the quantum vacuum. What can be learned from such experiments is not clear, since the experiments themselves are
not clearly designed yet. Anyhow experiments that seem just it gedanken experiments a few years ago, can be considered now as feasible for the next decade. Existing Petawatt lasers constitute one of the frontiers of physics and technology with important applications. But a future generation of multiPetawatt lasers will be able to analyze very fundamental physical problems. Most theoretical models suggest that there is an upper limit of the intensity attainable for a laser, the Schwinger limit. What is more relevant is that some designed lasers are not too far from that fundamental upper limit. The most important question now is to understand what will be the first features of the Schwinger limit that can be experimentally seen.

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