# Particle-in-cell study on positron production using lasers

Internship report, CELIA

Václav Hanus

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# Part I

# Introduction

In these days laser systems with femtosecond pulse length have become popular. At the same time people are more experienced with electron and ion acceleration experiments. It is not difficult to produce electron beams with energy about 10 MeV and more [1]. Realizing that energy the threshold for electron-positron pair production is about 1 MeV, investigation of positrons in laser-matter interaction started. On of the first works occupied with this topic was [14], where cross sections ans related processes were introduced. Positrons beams from laser sources, thanks to its higher density and energy, could surpass conventional sources. Therefore it could be used in astronomy studies on pulsars, gamma ray bursts as well as pair plasma investigation [10].

In fact, there are two ways how to make positrons with laser:

1. To accelerate electrons in a gas jet and let them undergo an interaction in a secondary solid target [5].

2. To create positrons directly in a solid target [4].

The second way seems to be simpler in point of view of experimenters, but processes are very complex making any preliminary calculation difficult, therefore attentive analysis is needed. For such an analysis particle-in-cell (PIC) code is known to be very useful since it covers many electron acceleration mechanisms.

In this internship in CELIA laboratory I was supposed to study laser-matter interaction in order to find optimal computational methods for positron estimation as well as to get more familiar with related physical processes.

For the theoretical part of work I should present interesting electron acceleration mechanisms involved and describe how positrons can be created.

For the other part I should learn how to use the particle-in-cell code PICLS and I should explore how this code could be useful for positron studies. I should be interested which target designs it is possible to simulate with PIC, if it is possible to use PIC for electron transport studies, which useful data one can obtain from such simulation and if one can obtain Bremsstrahlung data from PIC code or directly calculate positron production inside the code.

# Part II

# Research work

## 1 Laser-matter interaction

### 1.1 Laser absorption

At first, one must describe interaction of laser pulse with solid target. Usually before main high-intensity pulse impacts, the so-called *ASE* (*Amplified Stimulated Emission*) prepulse arrives and strikes the target. This prepulse causes target surface to evaporate creating a plasma with exponential density profile. In the case of titan sapphire laser it takes about a few ns before the main pulse reach the target, hence the preplasma can spread over several microns. The existence of the prepulse plays a very important role in the absorption of main laser pulse.

Laser absorption depends on the *critical density* given as

$$n_c = \frac{\varepsilon_0 m_{\mathrm{e}}}{e^2} \omega_L^2$$

where $\omega_L$ is laser frequency. One can get more useful form $n_c = 1.115 \times 10^{21} \lambda_\mu^{-2}$ cm$^{-3}$, where $\lambda_\mu$ is laser wavelength in microns. Importance of this quantity lies in a fact that laser does not propagate into regions with higher density than critical density. The region with higher density is called *overdense* *plasma*, the opposite is *underdense plasma*. In our case it means, that if there were no preplasma laser pulse could not be absorbed and would be reflected because of high density of solid matter (higher than $10^{22}$ cm$^{-3}$).

Characteristics of density gradient is also important in laser electron acceleration and is demonstrated with PIC in the figure 2 and in the article [9].

## 1.2 Electron acceleration mechanisms

Several mechanisms which lead to transmission of laser energy into kinetic energy of electrons have been already identified [1]. Their occurrence depends on conditions during the interaction for instance laser intensity, density or density gradient itself.

**Ponderomotive acceleration** works generally in each high intensity interaction. Steep spatial gradient of electric field causes nonlinear force. In non-relativistic regime over one laser period the force is given by formula:

$$\mathbf{F}_{\mathrm{pond}} = -\frac{e}{4m_e c^2}\nabla \mathbf{E}^2$$

In underdense plasma or plasma with gentle gradient one can distinguish two effects:

**Wake-field** stands for specific wave that develops in plasma when pulse duration is smaller than $2\pi/\omega_{\mathrm{pl}}$. Steep increase in electric field intensity pulls out electrons in longitudinal direction. As a consequence of this, an area with positive charge appears that attracts electrons and gives them energy. Such wave decays quickly, thus only accelerated electrons remain. This process is significant while accelerating electrons in gas jet target where electron density is lower than the critical one [6].

**Resonant absorption** occurs where plasma frequency is close to the laser pulse frequency. In addition target must be illuminated at an angle, thus the effect is not present at normal illumination. Near the *critical surface* (an area with density equal to critical density) electric field feeds an electronic wave and energy is absorbed by collisions.

The others are:

**Vacuum heating** which takes place when electron bounded to laser electric field gets into overdense region where the field disappears and electron gets free. Hence steep gradient of density is needed for this process. Works only in not-normal incidence but smaller intensity is sufficient. [3]

**$\mathbf{j} \times \mathbf{B}$ heating** basis of this process are similar to vacuum heating but this works for normal incidence and requires higher intensity. Electrons are accelerated due to magnetic part of Lorentz force. [17]

Presence of wake-field and $\mathbf{j} \times \mathbf{B}$ heating can be expected in 1D PIC simulation.

Important feature of non-thermal so called hot-electrons is that they can be characterized by exponential distribution with temperature $T_{\mathrm{hot}}$

$$f_{\mathrm{hot}}(E) \sim \exp\left(-\frac{E}{T_{\mathrm{hot}}}\right).$$

There are some tries to predict electron temperature in dependence on laser intensity. On that account we have got for example *ponderomotive scaling* or *Beg's scaling* [11]:

$$\mathrm{Ponderomotive}: T_{\mathrm{hot}} = m_e c^2 \left(\sqrt{1+\frac{I_{18}\lambda_\mu^2}{1.37}}-1\right) \mathrm{MeV} \tag{1}$$

$$\mathrm{Beg}: T_{\mathrm{hot}} = 0.46 \left(I_{19}\lambda_\mu^2\right)^{1/3} \mathrm{MeV} \tag{2}$$

Properties of these scalings are demonstrated in next paragraphs simultaneously with PIC predictions.

## 1.3 Electron refluxing

Once it has been shown how hot electrons are created a study of their propagation through a target is needed. In spite of the fact that the electrons gain lots of energy, they do not escape the target. Moreover, the majority of hot electrons stays in the target. One speaks about *refluxing efficiency* [12, 16] that gives a ratio between electrons bounded and escaped. In one dimension this can be described by simple *capacitor model*.

Let us consider the target as one plate of infinite parallel-plate capacitor. Then a detector in distance $d$ from the target stands for the second plate. Capacity of such a system is $C = \varepsilon_0/d$. At very beginning the target is neutral. If a few electrons having charge $Q$ escape from the target surface to the distance $d$, they create a potential barrier $\phi = Q/C$ which prevents others from escape. Consequently, only electrons with energy higher than $e\phi$ can escape. Number of such electrons eligible to leave the target is given by Maxwell-Boltzmann distribution $N_e = N_{\text{total}} \exp\left(-e\phi/T_{\text{hot}}\right)$. This leads to self-consistent equation

$$C\phi = eN_{\text{total}} \exp\left(-\frac{e\phi}{T_{\text{hot}}}\right). \tag{3}$$

If one knows total number of hot electrons $N_{\text{total}}$ and its temperature then solving this equation for $\phi$ can get ratio between those electrons escaped and those confined. Thus, refluxing efficiency is given as $\eta_r = 1 - \exp(-\phi)$.

Validity of this model will be examined with 1D PIC in later chapters.

## 1.4 Production of positrons

Generally, two ways exist how to make positrons from electrons. Both of them request presence of heavy atomic nuclei.

### 1.4.1 Bethe-Heitler process

During electron transport through a matter photons are created as a product of Bremsstrahlung. If a photon of energy at least $2m_ec^2$ transmutes to electron-positron pair, it is called *Bethe-Heitler* process. Thus, positron production is two step process.

The process takes place in field of atomic nuclei or electron. These particles are needed to retain part of momentum. If the momentum is overtaken by electron it is called *triple process* [13, 8] (do not confuse with *trident process*).

### 1.4.2 Trident process

Positron with higher energy than about 2 MeV [15] that passes around positive charge can produce electron-positron pair. As a result of this, so called *trident process*, are three particles. On the basis of theoretical study [2] one can obtain the cross section formula [7]:

$$\sigma_{\text{trident}} = 5.22Z^2 \ln\left(\frac{2.30 + E_0[\text{MeV}]}{3.52}\right) \mu\text{barn}$$

which could be particularly interesting for PIC positron calculation.

Author of an article [6] did an analysis of significance of these two processes. In general, one can say that trident process would be more important in thin target where the second process loses because of lack of radiation.

# 2 Particle in Cell

Plasma is quasi-neutral gas where particles attract or repeal themselves by Lorentz force which depends on electric and magnetic fields. It is not possible to take into account interaction between every pair of particles, therefore, a simplification is needed.

Let us divide the space containing charged particles by grid. After that we have got a set of particles in each cell having charge and making electric current. We can extrapolate these quantities into adjacent nodes of the grid and calculate electric and magnetic fields in the nodes. Afterwards, the movement of particles in the node neighborhood is calculated from equation of motion using fields taken from the node. Furthermore, there are no real particles but so called macro-particles. One macro-particle can stand for billions real particles. This algorithm is particle-in-cell.

This approach do not cover every phenomena within laser-matter interaction, since it does not include collisions, ionization processes, synchrotron radiation, Bremsstrahlung and so on. Anyway, some of these features can be added into the code to obtain the required functionality. From the point of view of positron research an addition of collisional or Bremsstrahlung module sounds good.

## 2.1 PICLS

PICLS is multipurpose PIC code written in Fortran and realized as 1D and even 2D. I have got familiar only with 1D version. Before starting a work with PICLS it is good to know that it uses a little bit different system of units. Unit normalization is described in table:

| Position | Time | Density | Electric field | Momentum | Charge | Mass |
|---|---|---|---|---|---|---|
| $\frac{\mathbf{r}}{\lambda}$ | $\frac{\omega t}{2\pi}$ | $\frac{n}{n_c}$ | $\frac{e\mathbf{E}}{m_e \omega c}$ | $\frac{\mathbf{p}}{mc}$ | $\frac{q}{e}$ | $\frac{m}{m_e}$ |

Where: $\lambda$ - laser wavelength, $\omega$ - laser frequency, $n_c$ - critical density. Useful to know is that for electric field in PIC units a formula $E = 0.85\sqrt{I_{18}\lambda_\mu^2}$ is valid ($I_{18}$ stands for laser intensity in $10^{18}$ W/cm$^2$ units).

Using PICLS I can simulate laser plasma interaction establishing three adjacent regions. In the middle region whatever density profile can be set by user routine. Once set also all other parameters I simulated my plasma and obtained physical quantities such as macro-particle position and momentum, real particle density and electric field.

I did a post-processing of output data to dig out some interesting quantities. I calculated kinetic energy of electrons using formula

$$\epsilon_{\text{kin}} = m_e c^2 \left(\sqrt{1 + p_x^2 + p_y^2} - 1\right).$$

Doing linear fit of logarithm of energy distribution I could get hot electron temperature. If the equation of found line is $y = kx + q$ then I can estimate temperature by formula $T_{\text{hot}} = {-0.511}/{k}$ MeV as illustrated in the figure 1.

For electric field holds true

$$E_x = -\frac{\partial}{\partial x}\phi$$

whence electric potential can be obtained integrating electric field in longitudinal direction.

When counting particles we must pay attention to the fact that macro-particles are weighted. This means that each macro-particle brings one additional property - weight. As a result of constant number of particles per cell, the density is controlled by this property. For instance, if a particle has weight $1/2$ it stands for half number of real particles. A particle which weights 1 represents

$$q = \frac{nL_{\text{cell}}}{N_{\text{cell}}}$$

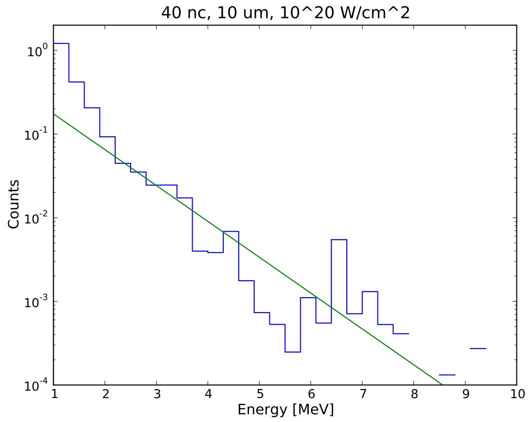


Figure 1: Example of temperature estimation from energy histogram using linear interpolation.

| # | $n_e$ | **Target thickness** [$\mu$m] | **Pre-plasma length** [$\mu$m] | **Target composition** | **Note** |
|---|---|---|---|---|---|
| 1 | 40 | 10 | 1 | H | Influence of preplasma length to hot electron characteristics. |
| 2 | 40 | 10 | 10 | H | |
| 3 | 40 | 10 | 10 | H | Vast region about 20 mm simulated. Potential and electron refluxing study. |
| 4 | 400 | 10 | 10 | H | - |
| 5 | 1200 | 1 | 10 | Pb | Solid density, degree of ionization $Z = 40$ assumed. |

Table 1: List of interesting simulations. For each simulation a set of intensities $\{10^{18}, 5\times10^{18}, 10^{19}, 5\times10^{19}, 10^{20}, 5\times10^{20}, 10^{21}\}$ was investigated.

real particles per unit of surface. Here $L_{\text{cell}}$ is length of one cell and $N_{\text{cell}}$ is number of macro-particles in one cell.

# 3 Computer experiment

In pursuit of exploiting the PIC code for positron purpose, I did several simulations whose list is in the table 1. Meaning of chosen parameters is explained in next few paragraphs. Every time I used laser pulse with wavelength $\lambda = 1\mu$m and duration $\tau_{\text{FWHM}} = 33$fs.

## 3.1 Hot electrons characteristics

I studied properties of hot electron depending on length of preplasma and incident laser intensity. For this purpose I did two runs. Their results can be seen in figure 2. First run consists of hydrogen target 10 microns thick with 40 $n_c$ density and exponentially decreasing preplasma with its characteristic length 1 $\mu$m. It means that density falls to $1/e$ of initial density in the distance 1 $\mu$m. Second run consists in a target having same parameters but preplasma scalelength 10 $\mu$m. I determined hot electron temperature, number of real electrons and laser energy conversion efficiency that is given by ratio of energy in hot electrons and laser energy. One comes to realize that presence of preplasma plays a significant role in hot electron generation as with long preplasma electron temperature increased and number of hot electrons too.

For positron research I should have investigated more dense and more heavy target. Thus, simulations for hydrogen 400 $n_c$ and lead of solid density were done. One can see in the picture 3 that the characteristics of electrons are very promising. However, PIC simulation in this regimes are very time demanding that is why only 1 micron target for lead solid density was chosen.

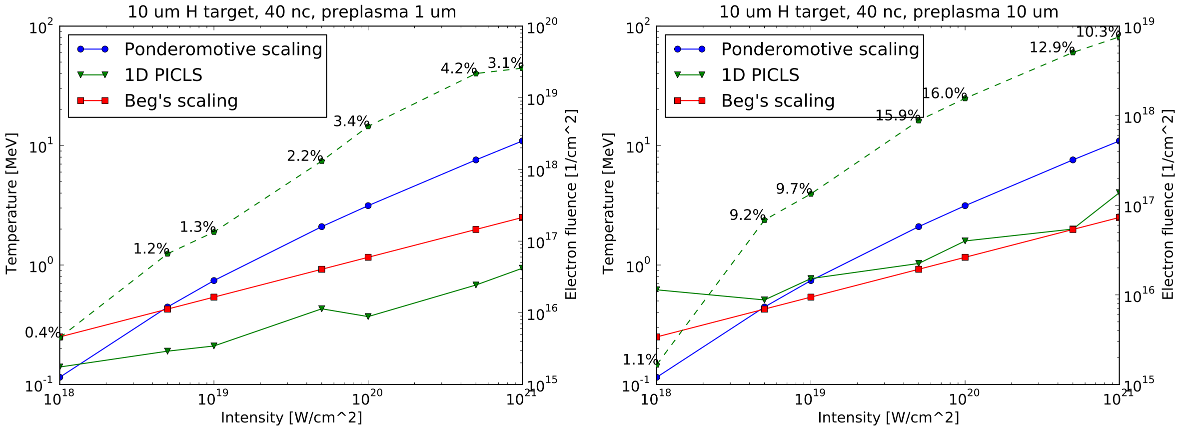


Figure 2: Illustration of preplasma length influence to electronic characteristics within illumination a target of $40\,n_c$ density. Triangles show temperature scaling obtained from PIC simulation. Dashed line presents number of created hot electrons. Adjoined percentage gives a ratio between energy in hot electrons and total laser energy. On the left preplasma length is only 1 $\mu$m and it can be seen that laser absorption is quite ineffective. PIC results are compared with quasi-analytical scaling formulas (1) and (2).

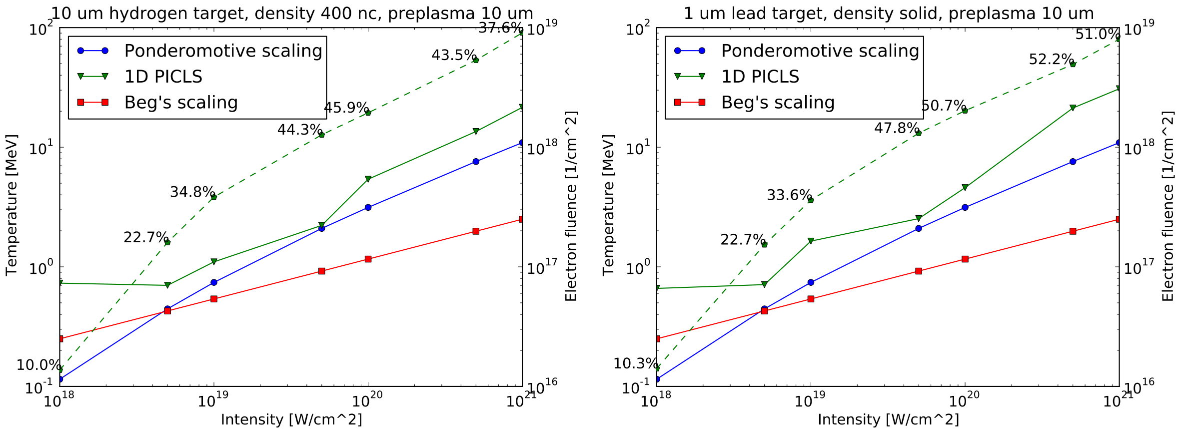


Figure 3: Meaning of symbols as described in figure 2. Acceleration in dense targets seems to be more effective according to PIC cell code.

## 3.2 Capacitor model in PIC

I will try to validate the capacitor model presented earlier in the section 1.3. For that purpose, I ran a simulation in a vast region ranging to several millimeters for high number of timesteps. Than I calculated electric potential in last moment. I fitted the potential with the capacitor one and I took a difference $\phi$ between two levels of potential and its distance $d$ as illustrated in figure 4. Now the question is whether this value agrees with solution of equation 3. For solution of this equation I took $T_{\text{hot}}$, $N_{\text{total}}$ and $d$ from PIC. Comparison of the potential from PIC and those from capacitor model is depicted in 4.

The solution of the equation 4 exhibits a lot of sensitivity to hot electron temperature as can be seen in the picture. Moreover, there was a problem with determination of temperature in long-lasting runs of PICLS. Many high energetic electrons appeared that made temperature estimation more uncertain.

According to capacitor model, refluxing efficiency in all studied cases is higher than 99 %. It was not possible to study this efficiency by PIC itself because of small number of particles in the simulation.

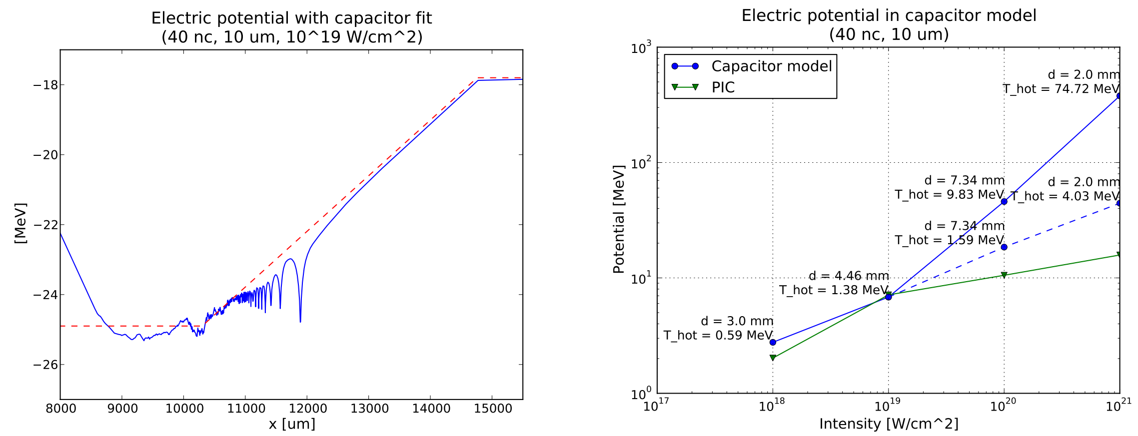


Figure 4: Long-lasting simulation: In the picture on the left dashed line shows potential of imaginary capacitor that is used in the model. Here the difference between the levels is 7.13 MeV. Target including preplasma lies within coordinates 10 000 and 10 079. Right picture shows comparison of potential from capacitor model and potential from PIC. For calculation of dashed branch $T_{\mathrm{hot}}$ and $N_{\mathrm{total}}$ from short time simulation are used.

# 4 Possibilities of positron calculations

Brute force would be to use a computer simulation based on PIC with all processes needed for positrons generation. This include Bremsstrahlung, cyclotron radiation, photon particle simulation, electron-ion, photon-ion and photon-electron collisions. PICLS is able to calculate some collisions so implementation of trident process in the code would be interesting. Trident process within PIC could be significant for the reason that many energetic electrons remain in the target. One could say that these electrons cannot produce positrons via trident process since the production threshold is about 4 MeV, however, as can be deduced from the left picture in the figure 4, there would be electrons up to 7 MeV. Moreover, for laser intensity $10^{20}$ and $10^{21}$ values of potential barrier are 10 MeV and 15 MeV respectively. Still, results come from 1D approximation and in the real case the barrier potential could be lower thanks to boundary effects.

Fast electrons that surpass potential barrier are also important for positron production despite its lower amount. They carry a lot of energy and they can flight through dense part of target where probability of pair creation is higher. Unluckily, 1D PIC simulation on ordinary PC does not yield too much information about this sort of particles. However, we can estimate their number from the knowledge of hot electron temperature, Maxwell-Boltzmann distribution and height of the potential barrier.

Since Bremmstrahlung and cyclotron radiation features are still in development in PICLS, it would be possible to calculate the radiation analytically as proposed in [11] from the electron spectra PIC gives us. Once we know electron and radiation characteristics we could finally employ Monte Carlo simulation to reveal number and properties of positrons in the interaction.

I propose to follow these steps for positron calculations:

1. Make a PIC simulation with trident process calculation included for thin solid target with preplasma whose parameters are in accordance with laser system in consideration.
2. Take paramaters of electrons bounded in target and calculate analytically radiation yield.
3. Use escaped electrons and radiation data to Monte Carlo simulation for thicker target than the one in PIC.

I assumed that refluxing do not depend on target thickness but in thick targets the situation should be investigated more deeply.

# Part III

# Summary

During two month internship in CELIA laboratory I deepened my comprehension of laser-matter interaction. That includes significance of preplasma to electron acceleration, electron acceleration mechanisms and electron beam separation processes.

I learned how to use PICLS programme where it is essential to manage well the system of units and to prepare input file without mistakes. While dealing with output data I acquired some knowledge on using Python programming language with its SciPy and MatPlotLib features which I have considered to be very useful and user friendly.

Using 1D PIC simulation I showed that preplasma of significant length is needed to obtain effective electron acceleration in overdense targets. Simple electron separation model based on planar capacitor was introduced that seems to be valid for lower laser intensity up to $10^{19}$ W/cm$^2$. However, its validity was verified only in 1D PIC pseudo-reality.

I also proposed how to use PIC results for positron calculations which should follow in the near future. It includes analytical evaluation employing *Continuous Slowing Down Approximation* model for radiation estimations as introduced in [11] and Monte Carlo simulation of transport of electrons and radiation that could be done for example with code *FLUKA*.

# Part IV

# Acknowledgments

I thank my supervisors Emmanuel d'Humières and Vladimir Tikhonchuk. To Emmanuel as a PICLS developer who was willing to help me with the code. To professor Tikhonchuk who was keeping his smile when I asked him the same thing for more times. Thanks also to Igor Andriyash for his Python advice.

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