



Centre Lasers Intenses et Applications

Unité Mixte de Recherche CNRS -CEA -Université de Bordeaux (UMR 5107)

<http://www.celia.u-bordeaux.fr>

Report on the thesis of Dominika Mašlářová in order to obtain a PhD in Physical Engineering of the Czech Technical University in Prague

Talence, April 20, 2024

Dominika Mašlářová conducted her research at the Department of Physical Electronics of FNSPE, CTU in Prague, under the supervision of Jan Pšikal and Miroslav Krůs. The subject of her thesis is **"New concepts in laser wakefield acceleration"**. This thesis work focused on the modeling of the acceleration of electrons and positrons to high energies in the wakefield produced by intense lasers propagating in low density plasmas and on the associated high energy radiation emitted in the X domain by betatron radiation, - a femtosecond synchrotron-like high-energy photon source, a natural byproduct of the laser wakefield acceleration of electrons. This thesis consists of a large number of simulations and theoretical interpretations, linked for some of them to experiments carried out at the Extreme Light Laboratory, at the University of Nebraska in the USA, and with experiments proposed on new ultra high intensity installations such as ELI Beamlines. The ambitious simulations carried out as part of this work are very well chosen and allow a precise and careful analysis of the main parameters controlling the acceleration of electrons and positrons, as well as the emission of high energy photons and their optimization in terms of brightness or efficiency.

This is a difficult subject because it requires solid knowledge of plasma physics, the physics of high intensity laser-plasma interaction and the physics of particle accelerators, as well as high performance computing. The optimization of laser wakefield acceleration (LWFA) of electrons and the associated betatron sources is a rapidly expanding field of laser-plasma interaction due to their very significant application potential linked to the compactness of the acceleration zone in comparison to the sources of high energy electrons using traditional particle accelerators. Therefore, it can be beneficial not only for large-scale infrastructures, such as the free electron laser or electron-positron collider, but also for small-scale research, medical, and industrial facilities. This thesis work thus made it possible to explore new avenues which will become increasingly important with the development of new high-intensity and ultra-high-intensity laser installations.

The manuscript is well structured. It is easy to read and an educational effort has been made in the first parts, as well as to explain the process necessary to obtain the results described. It is organized into two parts. The first part introduces the context of this work and in particular the issues of laser-plasma acceleration, as well as the objectives of the thesis. The theoretical concepts necessary to understand the acceleration of high-energy electrons in the wakefield produced by the

CELIA, Université de Bordeaux, 351 cours de la Libération, 33405 Talence cedex, France

Téléphone : +33 5 40 00 37 77 Téléfax : +33 5 40 00 25 80

e-mail: emmanuel.dhumieres@u-bordeaux.fr

propagation of an intense and short laser pulse propagating in a low density plasma are first presented. The creation of the wakefield, the injection and the acceleration of the electrons are described. Then the transverse motion of the electrons during their acceleration in the wakefield created by the laser and its influence on the characteristics of the betatron radiation emitted are detailed. The state of the art for the acceleration of electrons by wakefields and for the production of associated energetic radiation is exhaustive and up to date, therefore providing a broad overview of the latest developments in this field of research. This part consists of seven chapters. In Chapter 1, high intensity short pulse laser systems that are typically used for LWFA are described. Chapter 2 introduces the generation of plasma by intense laser pulses and the propagation of ultrashort ultraintense laser pulses in low density plasmas. In Chapter 3, the mechanism of wakefield generation is discussed in detail. Chapter 4 then focuses on the injection of electrons into the accelerating part of the wakefield. In Chapter 5, alternative laser-based and plasma-based methods of electron acceleration are presented. Chapter 6 offers a summary of secondary X-ray sources from LWFA electrons. Part I concludes with Chapter 7, which provides an overview of several promising applications of LWFA, and discusses the current limitations of LWFA.

Part II focuses on five new ideas related to LWFA and proposed in the framework of this thesis. The investigation was based primarily on the analysis carried out by numerical simulations. This part consists of two chapters. The first of them, Chapter 8, introduces the particle-in-cell (PIC) method, which was used in this thesis to simulate high intensity laser-plasma interaction. Several PIC codes were used to obtain the results presented in the next chapter (EPOCH, OSIRIS and SMILEI). Chapter 9 subsequently presents the main studies performed during the thesis. The first three schemes focused on the properties of the electron injection into the wakefield. The first concept suggests that a laser pulse, when focused into a super-Gaussian spatial profile rather than the conventional Gaussian profile, can self-produce in a controllable manner an ultrashort electron beam characterized by a substantial charge in the order of hundreds of pC. Next, a novel optical injection process, based on the collision of two laser pulses at an acute angle, is presented. The results reveal that the injection can occur in one of the respective wakefields, depending on the temporal delay between the pulses. This work is also supported by experimental results obtained by collaborators at the Extreme Light Laboratory of the University of Nebraska, Lincoln, USA. A follow-up study carried out within this collaboration examined the potential of injecting electron beams into both wakefields. In addition, the creation of ring-like electron structures was observed and explained. The fourth project aimed at the enhancement of the gain of betatron radiation. It focused on a novel method to enhance betatron radiation, based on the application of a local density increase at later acceleration times. This method offers an experimentally achievable increase of the radiation gain. The fifth proposal was targeted at the electron counterpart in a planned plasma-based electron-positron collider. It describes a novel setup where laser-generated positrons are injected into a plasma channel for further acceleration. Finally, a one-stage generation and acceleration of positrons with a highly intense laser pulse in a plasma channel was examined. More comprehensive descriptions of these concepts are given in the corresponding publications within the Appendix. These discoveries bring new insights into several aspects of laser wakefield accelerators and on ways to improve their overall performance.

These last chapters demonstrate that Dominika Mašlárová has a broad spectrum of knowledge and a real mastery of cutting-edge plasma simulation tools. The fact that she was able to complete the study of several relevant and difficult problems also demonstrates her good scientific maturity.

The results presented in this manuscript are summarized at the end of the manuscript, with discussions on possible applications of these results. The objective of improving the modeling of laser wakefield acceleration of electron and the associated high energy radiation has been achieved. The current limits of this work are well described and avenues for improvement are given. Perspectives are proposed for the continuation of experiments and research on the production of energetic electrons and positrons, as well as energetic radiation, with laser-plasma acceleration.

In conclusion, this work is correctly based on studies already published in the domain and the English used is very good. Overall, this manuscript is well organized and very well written. It constitutes a very good introduction to the modeling of the acceleration of electrons and positrons

to high energies in the wakefield generated by the propagation of intense and short laser pulses in low density plasmas and to the radiation emitted in the X domain by these electrons, but also to the simulation codes making it possible to model these processes realistically and in detail. It will therefore constitute a very useful and interesting basis for future students who will begin new studies on this subject. In addition, it provides very promising avenues for continuing this work at higher laser intensity with facilities like APOLLON and ELI. It is therefore an original and important contribution to the promising field of laser-plasma acceleration and the production of energetic radiation with intense lasers. The concern to systematically submit the numerical results to recent theoretical models, and the very appreciable concern brought to the analysis and preparation of experiments, are essential points of this PhD work. Two first-author publications associated to this work have already been published in international peer-reviewed journals, as well as two second-author publications.

I therefore strongly recommend the thesis defense of Dominika Mašlárová on "**New concepts in laser wakefield acceleration**".

Prof. Emmanuel d'Humières
Université de Bordeaux - CELIA
351 Cours de la Libération
33405 Talence
0540003777
emmanuel.dhumieres@u-bordeaux.fr