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Report on theoretical study of beam transport and FEL operation in the short pulse regime

Lead Beneficiary:

IST

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Deliverable Nature	
R = Report, P = Prototype, D = Demonstrator, O = Other	R
Dissemination Level	
PU = Public PP = Restricted to other programme participants (incl. the Commission Services) RE = Restricted to a group specified by the consortium (incl. the Commission Services) CO = Confidential, only for members of the consortium (incl. the Commission Services)	PU

A. Abstract / Executive Summary

Synchrotron sources and free-electron lasers based on laser plasma wakefield accelerators: Laser-plasma wakefield accelerators (LFWA) have been developed to the point where they can now be considered as a driver of next generation compact radiation sources. The most challenging electron beam driven source is the free-electron laser because of its unprecedented brightness and coherence.

The main objective of this deliverable is related to the overaching Task on Synchrotron and FEL sources, to pool experimental and theoretical efforts across the various groups to realise a LPWFA driven FEL; this deliverable is dedicated to theoretical aspects of this work.

This deliverable was executed by first, developing the numerical resources capable of accurately describing FEL radiation in laser-plasma context (IST).Transport of this beam was also tackled (Strath). Thanks to the additional degree of freedom that plasmas offer compared to classical undulators for tailored acceleration of particles, new schemes involving plasma channels (IST) and new Ion Channel Sources (Strathclyde) were proposed.

B. Deliverable Report

1 Introduction

The main advances for this deliverable were twofold: the upgrade of the numerical code OSIRIS, which is one of the main tools used by Laserlab team-members to guide them in experimental interpretation and design in the context of plasma accelerators; and theoretical work by Starthclyde, proposing novel geometries.

All this wok was guided by the advances made by Strathclyde in the experimental and theoretical part, as their state-of-the-art facility ran during these past years a program dedicated to plasma-based free-electron lasers.

2 Objectives

The goal of this deliverable is to create and use the numerical and theoretical tools to foster a programme

(1) to optimise the laser-plasma wakefield accelerator and beam transport

(2) to make it suitable for driving a free-electron laser or compact x-ray synchrotron source.

(3) theoretical studies of the FEL driven by ultra-short electron bunches and the build up of coherence

(4) including the effects of beam pipe wakefields.

(5) Investigating the injection of HHG source to control the FEL properties

3 Work performed / results / description

Beam transport and FEL operation in the short pulse regime has been studied numerically, and this development was assisted by experiments carried out by Strathclyde. On the accelerator stage, several aspects needed closer inspection: the mechanism for injection (for the optimization of the electron bunch in charge and shape), guiding of the beam during the acceleration, and the radiation losses as the electron energies increase.

In both plasma and laser-wakefield accelerators, the full understanding of injection remains an open issue. Controlling injection is crucial for the future of plasma-based accelerators since the accelerated beam properties and quality depend on it. Improving properties such as emittance, energy spread and angular spread (in which position relative to the axis electrons are injected) can be determinant to the injection of the beam into an undulator.

At IST, we first tackled Objectives 1 and 2, by using OSIRIS to model FEL-type plasma undulators.

IST deploys OSIRIS, a massive particle-in-cell code for laser-plasma interaction, which is one of the main simulation toolboxes for the plasma wakefield acceleration community.We started by mimicking the FEL micro-bunching and radiation buildup by comparing OSIRIS and GENESIS, a well-known code to simulate FEL parameters. Once the relevance for FEL studies of our PIC code was established, we moved on to modelling plasma-based solutions.

The study of the radiation emission in a plasma-wakefield accelerator scenario where a magnetic field is applied to assist the injection into the ion cavity was modeled with the particle in cell code OSIRIS [1]. Two- and three-dimensional simulations, supported by an analytical model, show that external static magnetic fields with suitable spatial profiles and amplitudes can relax the self-trapping thresholds in plasma based accelerators [2]. We also find that magnetic-field assisted self-injection can lead to the emission of betatron radiation at well defined frequencies [3]. This controlled injection technique could be explored using state-of-the-art magnetic fields in current/next generation plasma/laser wakefield accelerator experiments.

We also studied the effect of plasma shaping for the transport of the beam (see DL 32.9), and driving optical laser shaping, which we found were effective knobs for the control of the acceleration mechanism.

In parallel, at Strathclyde we have carried out both experimental and theoretical investigations of injection, characterization of the electron beam, LWFA driven undulator radiation emission in the VUV and also betatron radiation emission.

The injection work has included understanding the evolution of the bubble structure in injection. We have now obtained good comparisons with a reduced model showing injection and PIC code simulations using OSIRIS and WAKE. Direct measurements of the bunch structure by measuring coherent transition radiation, were also carried out, which confirm the substructure predicted by the injection model that we have developed. An experimental paper has been published on the role of the plume in the LWFA based on a plasma capillary [8,9]. A new diagnostic technique for measuring the plasma density in a plasma channel has been developed [7].

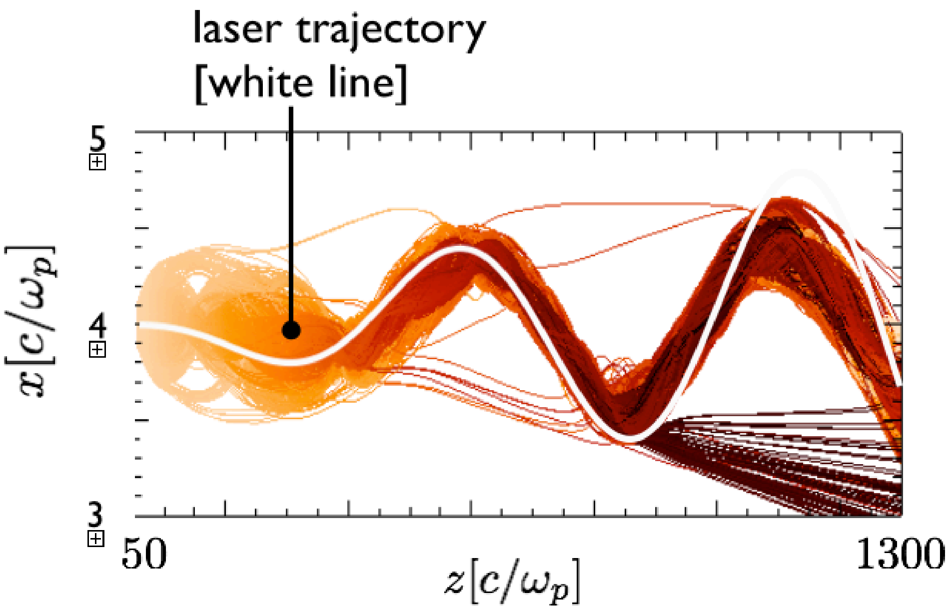

Figure 1. As the project started, OSIRIS was used to calculate particle trajectories in the case of corrugated accelerators, mimicking FEL effects.

Objective 3 was then tackled: the effect of radiation damping on the motion of particles in the ultrarelativistic regime was investigated [4]. Up to now such effects were not considered in PIC codes, but their impact needed to be taken into account. Several models were compared for the calculation of radiation damping force, with the goal of developing an algorithm for radiation damping in Osiris. A radiation damping algorithm was then implemented in OSIRIS.

The radiation package jRad, a post-processor to OSIRIS, is now fully operational, allowing for the calculation of radiation from accelerated particles including relativistic corrections due to electron recoil in moderate radiation cooling scenarios. The code was upgraded, changing the parallelization distribution, from the distribution of particles trajectories by the processes to the parallelization in terms of the detection pixels. Such an upgrade presently allows to account for coherence effects, which are revealed in the full calculation. In addition, the capability of determining the Stokes parameters and therefore the polarisation properties of the radiation emitted by relativistic particles was added. This feature enabled the exploration of production of high frequency (VUV to X-ray) polarised radiation sources.

Alternative sources of X-ray radiation based on plasma wigglers were also investigated. Radiation emitted from electrons wiggling in a corrugated plasma channel was investigated. The plasma channel corrugation leads to unconventional trajectories and radiation spectra distinct from usual setups with LWFA electron bunches in a plasma wiggler.

For Objective 4, advances made previously were explored to control particle trajectories in new plasma geometries. At IST, the upgraded version of OSIRIS was used to determine the behaviour of accelerated electrons in these new geometries, as in Figure1. At Strathclyde, experiments have been carried out to measure VUV radiation from a LWFA driven undulator. This shows that narrow spectral width synchrotron spectra can be produced using a quasi-monoenergetic LWFA beam. Undulator radiation in the wavelength range 150 – 260 nm has been produced by 1.5 fs electron bunches from a 2 mm long laser plasma wakefield accelerator. The number of photons measured is up to 9×10^6 per shot for a 100 period undulator, giving a peak brilliance of > 3×10^{18} photons/s/mrad^2/mm^2/0.1% bandwidth. The radiation pulse duration is as short as 3 fs for 120 – 130 MeV electron beams.

Starthclyde investigated in parallel betatron radiation sources. The theoretical investigations involve developing a unified theoretical model of betatron radiation. Experiments to characterize the betatron emission in a plasma channel have been carried out and published [5,11]. Investigations have been carried out on radiation reaction of particles in high fields [6,10]. This work has been published.

The final objective was to understand the importance of seeding in the design of the plasma-based FELs. This work was partially accomplished by the new developments in OSIRIS that now take into account coherence effects in the radiation, and radiation reaction of accelerated particles. However, to further explore the potential of large bandwidth and short pulse duration in FEL’s, IST is involved in an international collaboration led by Dr. Giovanni de Ninno, at INFN, a Laserlab associated partner, aiming to study the role of seeding with high harmonics of a laser in a free electron laser, in a chirped pulse amplification (CPA) geometry. CPA permits one to create bunching on a larger number of electrons, and to (approximately) linearly increase the output energy of the generated FEL pulse. In ideal conditions, the chirp carried by the phase of the seed pulse is transmitted to the output phase of the FEL pulse. Chirp compensation after the last undulator allows production of a short (ideally Fourier-transformed) pulse and, therefore, a larger peak power with respect to what obtained, for the same conditions, in standard (i.e., no-chirp-on-the-seed) operation mode. As an additional advantage with respect to standard operation, CPA can significantly shorten the final FEL pulse duration with respect to standard operation. An experiment led by Dr. Giovanni de Ninno, at INFN was carried out at FERMI-ELETTRA in April 2015, to test this concept.

Finally, the work carried out in Objectives 1 to 5 led to many advances in FEL and synchrotron sources that open new perspectives for plasma-based FELs, not foreseen at the beginning of the project. For example, large scale magnetic field generation during the acceleration of electron bunches in the laser wakefield accelerator was investigated numerically and theoretically in the conditions of recent experiments performed at LOA. This worked showed that intense magnetic fields were produced at the boundary between the ionised plasma and neutral region resulting from hot electron currents produced during plasma wavebreaking. [7]The conditions for a plasma based FEL based on betatron radiation have been determined analytically and through particle-in-cell boosted frame OSIRIS simulations, which captured coherent radiation emission and amplification. The resulting electron beam bunching was also observed. This work also determined key electron beam conditions for lasing, in terms of its energy spread and transverse emittance [8].

Recently, beams with orbital angular momentum have started being used in laser-plasma interaction experiments. It remained to be seen if Laserlab teams could talked them theoretically and through simulations. We have investigated a novel positron acceleration regime using twisted laser beams with orbital angular momentum. It has been shown that intense and exotic lasers can drive doughnut shaped plasma waves suitable for high gradient positron acceleration, thereby giving a solution to a key challenge for future high energy physics applications [9].

4 Conclusions

We successfully delivered the theoretical studies that were proposed, tackling FEL physics with simulations and the support of experiments. As could be predicted, once the tools were set in place to study the classical geometries, immediately novel solutions that made use of the additional degrees of freedom offered by the plasma medium started to be explored. This work is very promising and may lead to exciting new discoveries in plasma-based secondary sources of ultra-bright radiation.

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