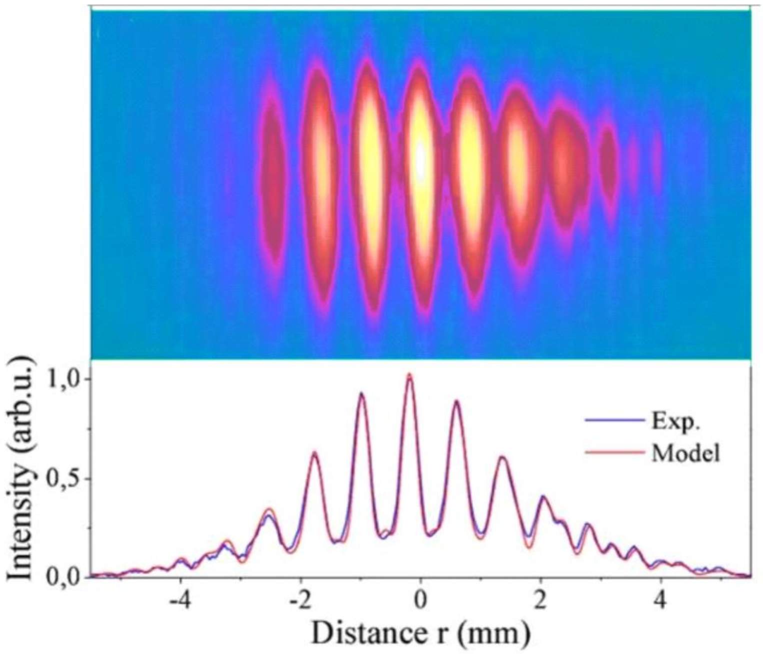

2013 Scientific General Document

CONTENT

Composition of the Working groups of the Institute for Lasers and Plasmas:

General coordination: Ph. Martin

Electron acceleration : B. Cros, resp.

sandrine.dobosz@cea.fr; Arnd.Specka@llr.in2p3.fr; delerue@lal.in2p3.fr; bruni@lal.in2p3.fr; rimbault@lal.in2p3.fr; mailto:marie-emmanuelle.couprie@synchrotron-soleil.fr; jean-raphael.marques@polytechnique.fr; xavier.davoine@cea.fr; mailto:brigitte.cros@u-psud.fr; gilles.maynard@u-psud.fr; victor.malka@ensta.fr; pascal.monot@cea.fr; Philippe.martin@cea.fr ; Laurent.GREMILLET@CEA.FR ; mailto:antoine.chance@cea.fr; Patrick.mora@cpht.polytechnique.fr; Jerome.schwindling@cea.fr;

Ion acceleration : J. Fuchs, resp.

tiberio.ceccotti@cea.fr ; pascal.monot@cea.fr ; Philippe.martin@cea.fr ; Patrick.Audebert@polytechnique.fr ; Julien.Fuchs@polytechnique.fr ; gerardmourou@gmail.com, dhumieres@celia.u-bordeaux1.fr ; tikhon@celia.u-bordeaux1.fr ; Laurent.GREMILLET@CEA.FR ; patrick.mora@polytechnique.fr ; victor.malka@ensta.fr ; alessandro.flacco@ensta.fr ; Laurent.GREMILLET@CEA.FR ; BALDACCHINO Gerard; RENAULT Jean-Philippe ; lorenzo.romagnani@polytechnique.edu, erik.lefebvre@cea.fr, gerald.faussurier@cea.fr, enl@cenbg.in2p3.fr, batani@celia.u-bordeaux1.fr, patrick.mora@cpht.polytechnique.fr

X-ray sources : Ph. Zeitoun, F. Quéré, resps.

davide.boschetto@ensta.fr ; philippe.zeitoun@ensta.fr ; Kim.Taphuoc@ensta.fr stephane.sebban@ensta.fr ; antoine.rousse@ensta.fr ;pascal.monot@cea.fr ; Philippe.martin@cea.fr fabien.quere@cea.fr ; marie-emmanuelle.couprie@synchrotron-soleil.fr ; kevin.cassou@u-psud.fr ; gilles.maynard@u-psud.fr ; david.Ros@u-psud.fr ; sophie.kazamias@u-psud.fr ; annie.klisnick@lixam.u-psud.fr ; olivier.guilbaud@u-psud.fr ; brigitte.cros@pgp.u-psud.fr ; Patrick.Audebert@polytechnique.fr;

High-Field physics : A. Di Piazza, resp.

Antonino Di Piazza <dipiazza@mpi-hd.mpg.de>; mickael.grech@gmail.com; Alfred Maquet <alfred.maquet@upmc.fr>; Natalia Naumova (natalia.naumova@gmail.com); Gérard Mourou [gerardmourou@gmail.com], philippe.martin@cea.fr ; patrick.mora@cpht.polytechnique.fr ; Laurent.GREMILLET@CEA.FR

PREAMBLE

CILEX (Centre Interdisciplinaire Lumière Extrême) is the Interdisciplinary Center on EXtreme Light. This center will be based at l'Orme des merisiers (France) and comprises three entities: i) the APOLLON laser which will deliver pulses at a still unreached instantaneous power of 10PW, ii) the associated infrastructures and experimental set-up and, iii) two 100TW class lasers, so-called "Satellite Facilities" (UHI100, LASERIX) allowing for an efficient preparation of experiments on APOLLON and the training of the scientists and engineers. Beside, two additional satellite facilities, Salle-Jaune (based in ENSTA) and ELFIE (based in Ecole Polytechnique) are volunteers to participate in the CILEX scientific program.

The French Ultra-High-Intensity community, working since 15 years on their satellite facilities has obtained in the past few years remarkable results on, for example, the generation of X-ray sources, the acceleration of electron beams over a few millimetres and the acceleration of ion beams from solid targets.

The APOLLON laser source will deliver 150 J in 15 femtosecond pulses (10 PW). After focussing, intensities up to 2×10^{22} W/cm^2 will be delivered to the experimentalists. This will allow reaching the so-called "*ultra-relativistic regime*" in which electrons and ions are both expected to be relativistic and thus allowing for the exploration of novel matter properties.

Now, scientists gather their efforts on two complementary aspects: getting a deeper understanding of the basis for this new physics and promoting related applications.

CILEX federates eleven laboratories[1] gathering all the skills necessary for the construction of APOLLON, the construction of the experimental set-up and the exploitation of the whole facility. Our vision is to operate APOLLON laser to its maximal capabilities and to attract new users communities, national and international, with the help of well-equipped dedicated experimental areas and fully instrumented beam-lines.

In this document, we intend to present a general scientific program to be developed in CILEX, as elaborated by the different working groups of the Institute Lasers and Plasmas without regarding too much technical details, budget or scheduling constraints. This document is supposed to be a fast evolving one and corresponds only to a picture snapshot of the CILEX scientific project in 2013.

[1] Laser and plasma laboratories: IRAMIS, LCFIO, LOA, LULI, LPGP, CPhT, LUMAT, high-energy-physics laboratories: IRFU, LAL, LLR and the Synchrotron radiation facility SOLEIL. The overall involved community is about 200 people including PhD students, post-docs and CDD.

INTRODUCTION

High-intensity lasers are the best compact tools to produce in a controllable manner, electromagnetic fields with not only the highest achievable amplitude but also the shortest duration. Consequently, a whole range of high-energy particles (electrons, protons, highly charged ions, neutrons) and radiation, up to x-rays and γ-rays can be produced as a result of the interaction with targets that can be either solid or gaseous.

Studying interaction using higher and higher intensities is of fundamental interest because it continuously opens the gate to unexplored regimes, like in particle acceleration or atto-second X-ray sources. Another motivation for the scientific community, is that the generation of such particle and radiation beams, intrinsically synchronised with the laser beam that has generated them, opens an extremely wide range of applications. Progress in fundamental physics, material physics, single-shot nano-scale imagery are daily growing up and there are now realistic perspectives for practical applications in medicine and life sciences, in time-resolved probing of matter under particle irradiation or as cost-reduced compact accelerators.

It must be clearly understood that the gain of 3 orders of magnitude in intensity allowed by the APOLLON facility with respect to more conventional intensities as obtained on the satellite facilities pushes the limit of the conventional optics toward new territories close to particle and theoretical physics. This is quite a new landscape and it is now mandatory to gather this laser physics with other disciplines, as high-energy-physics. This adventure is possible due to the unique combination of skills and equipment of the different partner laboratories involved in the project.

In the Ultra-High-Intensity physics community, there is also a very strong coupling between the experimental and the numerical-theoretical expertise. Many of the partners of this project have a solid experience in modelling ultra-intense laser-matter interaction over a wide range of laser and target conditions. For this scope, relativistic particle-in-cell numerical codes are developed and used in parallel with analytical models. These codes benefit from the state-of-the-art computing resources available at the CEA/DAM, on the open « Centre de Calcul pour la Recherche et la Technologie » (CCRT) computer centre and at IDRIS/CNRS facility. In addition, a strong collaboration between physicists and computer engineers is starting in the framework of the “Maison de la Simulation” (*www.**maisondelasimulation**.fr*) recently created. Our aim is to develop big computational codes adapted to extensive simulations on very large scale computers. Experimental results obtained on APOLLON will promote and help the further development of these codes in particular in the ultra-relativistic regime. On the other hand, calculations carried out in preparation of the experiments will favour the choice of the best parameters for the beams delivered to the users, and reliable numerical models will help the interpretation of the data collected in the experiments.

LASER PLASMA ELECTRON ACCELERATION

Spectacular progress has been made during the last 15 years in our understanding and mastering of laser based plasma acceleration processes. Among these processes, let us cite the non-linear propagation of UHI laser pulses in plasmas, non-linear wakefield excitation, relativistic self-focusing, or self-temporal compression. All these processes are strongly interdependent and a huge amount of work is still necessary on the fundamental side to provide the optimum conditions for an attractive and reliable electron accelerator which could reasonably compete with accelerators devoted to high energy physics or to the conception of an X-ray Free Electron Laser.

These achievements, mainly due to the accuracy of the experiments on high rep-rate 100 TW class lasers and to their essential coupling with numerical large scale PIC simulations, are impressive. Laser guiding in a plasma channel over a few centimeters has been shown to produce electrons accelerated in the GeV range [Leemans]. In the non-linear regime, the injection of the electrons in the accelerating field produces electron bunches shorter than the laser beam itself, with energies on the order of a few 100 MeV in a few mm long gas jets [Faure]. These relativistic electron sources are now to a certain extent mono-energetic, ultra-short (few fs), stable and tunable.

The laser-plasma electron acceleration program on CILEX will grasp the opportunity of the APOLLON laser to explore new acceleration domains. With the support of the satellite facilities, we expect to improve the electron beam characteristics in terms of energy, pulse duration and beam luminosity. On APOLLON, a dedicated electron beam line will be developed and implemented permanently. On this line, after a conception phase and tests on satellite facilities, diagnostics of the spatial and spectral beam profiles, of the emittance, pulse duration and charge will be implemented. After characterization of the beam, a specific electron beam line consisting in dipoles and quadrupoles will be constructed to transport the beam for specific applications as the injection in a secondary acceleration stage, the injection in an undulator for beam diagnostics or for photon production and for future studies on fundamental processes as non-linear Compton scattering, relativistic harmonic generation, betatron radiation, pair-production.

SINGLE-STAGE LASER PLASMA ACCELERATION

In the blow out regime of laser wakefield acceleration, advanced simulations as for example, three-dimensional boosted frame simulations in OSIRIS [Martins], or WARP [Vay], have addressed a broad range of parameters, from strongly nonlinear scenarios at 10 PW, to weakly nonlinear configurations at 1 PW, with propagation distances ranging from 2mm up to 5m. Results confirm the predictions from the phenomenological models [Lu], in particular the possibility to produce electron beams with tens of GeV's.

The availability of 1-10PW laser beams with pulse duration down to 15fs will open the way to unexplored experimental regimes. By varying the laser intensity (from 10^{18} to 10^{22} W/cm²) and the plasma density and length, it will be possible to explore a wide range of configurations, from the situation where the laser pulse is predicted to be self-guided to a regime where the pulse duration is much shorter than the plasma period. Simulations will be performed to design experiments in the 1-10PW range and will be a first comparison to scaling laws in the experimentally reachable range.

Betatron radiation is expected to be a rich diagnostic of the electron acceleration process, as well as an extremely bright source of hard x-rays or gammas (see X-ray sources for physics and applications).

MULTI-STAGES LASER PLASMA ACCELERATION

Multi-stage laser plasma acceleration [Schroeder] is a design of laser plasma accelerator which provides ways of controlling the properties of accelerated electrons and scaling up their energy by the addition of more stages. In this scheme, the injection and acceleration processes can be optimized independently. Electrons as well as positrons can be externally injected and accelerated in a laser plasma accelerator driven in the quasi-linear regime of laser wakefield.

The design planned as a first demonstration in the frame of CILEX will consist of an optical injector and an acceleration plasma stage. A controlled and reliable laser-plasma electron source will be developed, transported and focused at the entrance of a laser plasma accelerator.

The electron energy gain over the dephasing length in a quasi-linear laser plasma accelerator is inversely proportional to the plasma density. As the dephasing length, which is the length over which the electrons gain energy before slipping into decelerating fields, increases for lower density, the development of long plasmas with low electron density is required to increase the electron energy. Typically meter long plasmas at an electron density of $10^{17}cm^{-3}$ enable electron acceleration to several GeVs with a few PW laser pulses. Two types of methods can be used to counteract laser diffraction: non-linear effects, like self-focusing, operating at a power above the so called critical power and external guiding, which can be provided either by a preformed plasma profile in the transverse direction, or by a waveguide with metallic or dielectric walls, such as capillary tubes.

The development of meter scale plasma at low density inside capillary tubes will be undertaken: guiding in capillary tubes can be performed at low plasma density, it can be extrapolated to long length, and there is a local expertise. Long plasma targets will be constructed and tested at existing facilities before implementation on APOLLON. Other schemes like plasma channels created by discharge inside a capillary tube will be tested. Moreover, profiled capillaries will be used to control the longitudinal density profile at both ends of the capillary. This will be mainly developed through a collaboration with Romania (NILPRP institute), experts in plasma discharge technics, where, as a first step, the propagation will be studied using the already operational 30 TW laser facility and later on CETAL which is the newly installed PW system in Romania.

The implementation of a two stage laser plasma accelerator involving a 1 PW and a 10 PW beam, two plasma targets and an electron transport beam line between the two accelerator stages will require the development of new instruments for the diagnostics of electrons and radiation. Several challenging issues will have to be addressed to maintain a high average accelerating gradient between the two stages, and to achieve reliable electron acceleration, such as the preservation and characterization of the longitudinal, and transverse dimensions of the electron bunch between the two stages, and the stability in space and time of the laser and electron beams.

On a longer term a two stage laser plasma accelerator platform offers various opportunities to study the physics of laser plasma acceleration: injection of controlled multiple bunches produced in the first stage could be used to study their acceleration in adjacent plasma buckets of the quasi-linear plasma wave of the second stage; the production of two electron beams in the first stage could be used to study beam plasma acceleration driven by the first electron beam in a long laser preformed plasma. Simulations will have to be undertaken, to evaluate the feasibility of such schemes with the specific parameters of APOLLON.

Positron production and acceleration

A possibility for producing electron-positron pairs (see the Section related to *high-field physics* for more information on the mechanisms responsible for pair creation) relies on the interaction of energetic electrons with high-Z ions (pair production cross-sections indeed increase with the ion charge). This has already been demonstrated by focusing 10^9 (~60pC) laser-wake field-produced electrons in a low emittance beam with average energies of 3 MeV and maximum extending to over 12 MeV onto a lead target. It has been observed about 10^6 positrons per pulse with energy of 2 MeV [Gahn].

Considering APOLLON at the PW level, focussed in a plasma of density 2×10^{19} cm^{-3}, simulations show that high charge (~20nC) electron bunches with energy above 500 MeV will be achieved (see "First two years CILEX Scientific program"). Clearly, focusing such a beam in a high Z converter will be an interesting track to produce energetic and abundant positron source.

If successful, these experiments could lead to the next step which would consist in injecting the positrons beam into the second laser plasma acceleration stage.

Coupling to an undulator

Synchrotron radiation is emitted by charges accelerated particles of normalised energy γ, for example submitted to the magnetic field of a bending magnet in conventional accelerators. Undulators producing an alternate periodic permanent magnetic field B_u of period λ_u are intense source of radiation on third generation light sources. For example, 25 insertion devices are presently installed at SOLEIL, enabling to cover several orders in magnitude in the spectral range, with spectral brightness reaching up to 10^{20} ph/s/mm^2/mrad^2/0.1 % bandwidth. The majority of the undulators have been built in house by the magnetism and insertion device group of SOLEIL, which has also installed the first PrFeB based cryogenic undulator operating at 77 K [Benab1, Banab2].

A typical spectrum of radiation is shown in fig. 1a. The radiation generated in the different periods of the undulator interferes constructively, leading to a line spectrum. The undulator emits radiation at the wavelength λ_r and its harmonics of order n of the resonant wavelength. **The spectrum line shape and width depend on the electron beam parameters** (emittance and energy spread), as illustrated in Fig. 1b-e. The energy spread enlarges symmetrically the line with respect to its natural relative bandwidth given by the inverse of the harmonic number multiplied by the number of undulator period. The emittance contribution introduces a red-shifted sideband in the spectral distribution. **In consequence, besides being an intense source of radiation, the undulator emission constitutes a precise diagnostic of the electron beam properties**.

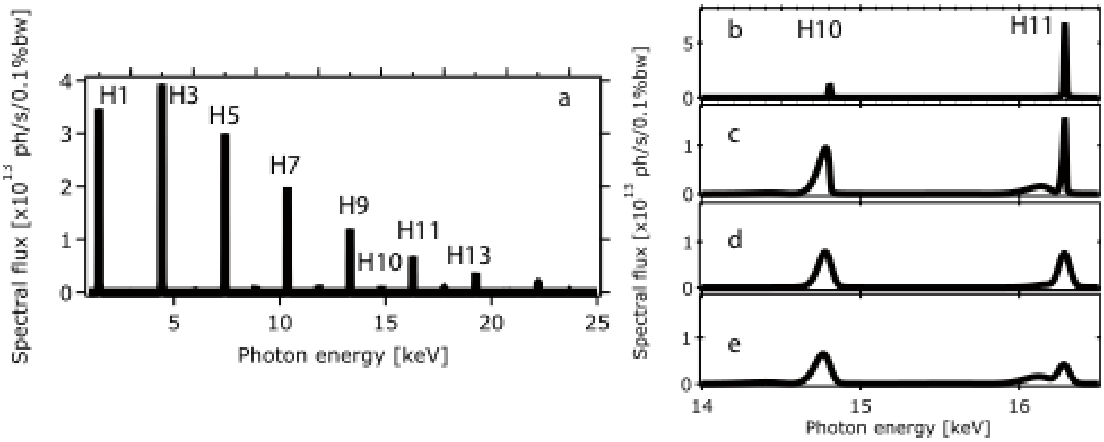

Fig. 1 : Example of in-vacuum undulator radiation : a) On-axis spectrum calculated for a filament mono-energetic electron beam Case of planar undulator with 100 periods of 2 cm, a deflection parameter of 1.8, with a 2.75 GeV, zero energy spread and emittance, b to e : Zooms on the tenth and the eleventh harmonics with a filament mono-energetic beam (b), a thick (emittance 4 nm.rad) mono-energetic beam (c), a filament non mono-energetic beam (energy spread of 0.1 %) (d), a thick and non mono-energetic beam (energy spread of 0.1 % and emittance of 4 nm.rad).

It is then natural to consider the injection of a laser wakefield accelerated electron beam in an undulator for both analysis of the electron beam properties and for the generation of spontaneous emission in the X-ray range. Spontaneous undulator radiation has already been observed in the various places, down to the VUV [Schlenvoigt, MFuchs]. Great hope can even further but put in these new accelerators in the prospects of compact free electron laser sources [Nakajima]. However, the present characteristics of the electron beam generated by plasma laser, in particular the 1 % maximum value of the requested energy spread and the large divergence, prevent straightforward amplification. Different beam manipulations, such as in transverse the strong focusing just after the gall cell generating the electrons and in longitudinal the electron sorting with a magnetic chicane [Maier] and supermatching [Loulergue] or with an undulator with transverse gradient [Huang, Smith] now enable in theory to get some amplification.

It is planned to study the use of undulators for electron beam produced by laser from satellite facility or APOLLON. Detailed design for a demonstration experiment of FEL amplification using the “salle-jaune” satellite is under study, with the transport magnetic elements and diagnostics, while using first an available 2 m long in-vacuum undulator, and then a cryogenic 3 m long undulator as shown in fig. 2 . External extra injection of harmonics - from gas or plasma mirror- to seed the signal is also considered. [Lambert].

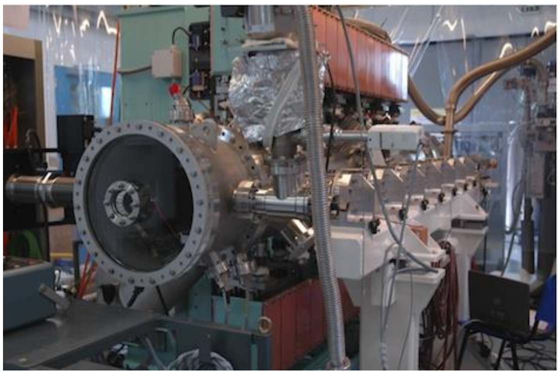

Fig. 2 : PrFeB cryogenic undulator developed at SOLEIL

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Laser plasma ion acceleration

Since the eighties, when the first MeV proton bunches from the interaction between a high-power, nanosecond laser, has been reported [Gitomer], spectacular progress has been achieved in the domain of laser-based ion acceleration. These advances are mainly due to improvement of the laser beams characteristics, especially in terms of duration (increasing the peak power), of the time-contrast preventing the formation of uncontrolled pre-plasmas [Levy], and ability to focus on small surfaces with the help of adaptive optics.

Nowadays, high-quality proton beams are produced from thin foils irradiated by UHI short laser pulses [Fuchs]. Even though still far from the performances achieved on large-scale accelerators (e.g. GANIL), these ion beams are laminar, collimated (about 30°), have duration at the source of the order of a picosecond and can reach energies in the 15 MeV range on typical satellite facilities. As a consequence, these beams are already being considered or applied in high-resolution radiography, for nuclear physics, or the production of high-energy-density matter of interest for astrophysics, and could also lead to high-brightness injectors for accelerators or sources for proton therapy or radioisotope production.

In the standard (i.e. the so-called Target Normal Sheath Acceleration (TNSA)) regime [Wilks], laser light focused to high intensity on a solid target surface can be efficiently absorbed by the electrons, resulting in a current of relativistic electrons streaming from the laser-irradiated surface into the target. These electrons have enough kinetic energy to exit into vacuum on the non-irradiated “rear” target surface, and set up a large electrostatic sheath at the steep solid – vacuum interface. This field ionizes atoms in the vicinity of the surface and accelerates them to energies that can be several times larger than the typical electron kinetic energy. This TNSA mechanism has been demonstrated and studied experimentally and numerically by many groups. It is able to produce a remarkably well-collimated proton beam, with a small emittance and a typical efficiency (laser energy to ion energy) of a few percents. At the moment, the state of the art in term of proton energy ranges from 17 MeV for 100 TW-fs class satellite facility [Zeil] lasers to 60 MeV for PW-ps laser systems [Snavely]. Different theoretical works have predicted that under particular interaction conditions (ultra-high contrast, high intensity and circular polarization) radiation pressure acceleration (RPA), or the light sail regime [Macchi] could replace standard TNSA. We intend to study this mechanism and then possibly increase the proton energies to the GeV range.

As for the electron acceleration program, the ion program will take the opportunity of using for the first time a clean (high contrast, perfectly focused) 10PW laser system to extend the limit of laser-accelerated protons into new domains, putting in evidence some new physical regimes originating from both relativistic character of electrons and ions.

According to scaling laws based on existing simulations, it could be also envisioned, using ultra-tight focusing of the 10PW laser in order to exceed 10^{23} W.cm^{-2}, to extend the energy limit to the GeV level. This will be tested uniquely on APOLLON.

From the application side, the scientific impact is inherently broad for a highly reproducible and controllable proton beam of several hundred MeV. This new and powerful source will unlock *innovative, high-impact applications such as radiography of dense objects with picosecond resolution, spallation with very small source size, study of the physics of ion beam interaction with a plasma (multi-ion interaction with non-degenerate matter), or relativistic laboratory astrophysics. It will allow entering into the regime of high-energy nuclear physics and possibly help realize medical applications.*

Considering the long term objectives on this subject with the APOLLON laser, the broad picture is described hereafter.

First couple of years of operation of APOLLON : Basic studies at 10^{22} W/cm^2

At currently available, moderately relativistic laser intensities, laser-based ion acceleration proceeds in the TNSA scenario. In the multi-PW regime, for intensities of the order of 10^{22} W/cm^2, new acceleration mechanisms will be within our reach allowing for larger laser-to-ion energy conversion efficiency, ion energies as well as a better control of the resulting ion beam properties. Among these mechanisms, direct acceleration of thin (sub-micron) targets by the strong radiation pressure [Esirkepov, Grech4] and directional Coulomb explosion of ultra-thin (nanoscale) targets [Grech5] will be within our reach.
As detailed in the so-called "First two years CILEX scientific program" document, firing thin foils in this regime of intensity will be our first step.

Relativistic laboratory astrophysics

Having the possibility to produce dense beams of very high energy ions (i.e. close to the relativistic regime) will allow uniquely to perform laboratory experiments aimed at understanding the processes that lead to emission of high-energy radiation and energetic particles from powerful outflows of astrophysical sources (supernovae remnants (SNRs), micro-quasars, Gamma-ray bursts (GRBs), pulsars, blazars,…) interacting with ambient magnetic field and matter [Bulanov]. Such outstanding unresolved issues have motivated deploying large experiments [http://www.mpi-hd.mpg.de/hfm/HESS/] when, using Apollon-produced beams, these could be studied in the laboratory. In particular, we could study the production of energetic particles and radiation in colliding high-energy outflows, by simply generating two of such expanding and counter-streaming magnetized plasmas.
Having the possibility for the first time to study all these effects in the laboratory is a great challenge and can bring significant new results to compare with the existing observations.

Warm and Dense Matter basic studies

Bundles of short-duration (<50 ps) high-energy proton generated by a high-intensity short-pulse laser are ideal candidates for heating solids or plasmas to high temperatures. In these conditions, the characteristic time of hydrodynamic expansion is effectively very long (100s of ps) compared to the duration of the proton bundle [Mancic].
Producing and probing matter with a density close to or larger than solid density at temperatures from a few eV to a few 100 eV will give new insight in this much unknown warm dense state of matter.

Stopping power in matter and plasma

Some crucial points relevant for inertial confinement fusion may be addressed on high-energy short-pulse laser facilities. Indeed, such mechanisms as heat and hot electron transport in hot plasmas, ion and alpha particle stopping power in hot and dense plasmas are either entirely unknown or still miss conclusive quantitative experiments. In addition to the interest for fundamental physics, knowledge and understanding of the mechanisms of slowing of ions and charge equilibrium are required either for conventional fusion, or for Fast-Ignition.

Performing such experiment with short-pulse high-energy particle beams would open for the first time the possibility to test models of energy loss in correlated plasmas for which there is no experimental data [Nuckolls].

Proton Radiography

Radiography using both x-rays and protons, with picosecond time resolution, has been very beneficial in elucidating basic phenomena in laser plasma interactions. In particular, protons have added new diagnostic capabilities since they are sensitive to electric and magnetic fields as well as plasma density [Mackinnon].

The production of higher-energy proton beams will give access to longer and higher-density plasmas relevant for laser-plasma interaction physics and high-energy-density physics.

Time-dependent irradiations in chemistry

Reaching a proper understanding of the dynamics of fast ionization of water when irradiated by energetic ions is crucial for a wide range of applications like e.g. energy production (nuclear fission), medicine (hadrontherapy) or space travel. The ion interaction with water is characterized by the so-called Linear Energy Transfer (LET) that is as: LET=(dE/dx) [Spinks]. Quantify the LET and its effects on matter, in particular in the context of the radiolysis of liquid water, and doing it in a time-resolved manner is the ultimate goal here as it would yield the time-dependence of the diffusion and reaction processes at play.

Our objective with the present thematic is to make use of laser-accelerated ion beams to advance our understanding of the radiolysis of liquid water. In particular, we want to study the spatial distribution of the energy the ions deposit into the water, as well as the resulting state of the water (excited, ionized –and at which levels, etc.), all this in a time-dependent fashion. As mentioned above, this is difficult to use traditional ion sources, such as conventional particle accelerators, mainly due to the fact that the temporal duration of the ion pulses from these sources is much longer that the characteristic times of ionization and electronic excitation. We propose here a new and alternative approach that will exploit the unique characteristics of laser-driven ion sources, and in particular their short pulse duration and their ease to be coupled and synchronized with short-pulse laser probes.

We expect this program to have a significant impact on the field of water and solid material radiolysis since *they will yield the first time-dependent ultra-short measurements of the mechanisms at play* [Baldachinno].

NEUTRON SOURCES

Beside ion sources, we also plan to develop neutron sources by inducing nuclear reactions in hot plasmas. *This will give users access to unprecedented short neutron bunches, not available on conventional facilities such as neutron tubes or spallation sources.*

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X-RAY SOURCES FOR PHYSICS AND APPLICATIONS

Within all the developments achieved so far on satellite facilities, short-wavelength sources cover a wide range of photon energy, from typically 30 eV to tens of keV, with a total emitted energy per pulse from a few nanojoules to a few millijoules and pulse durations ranging from a few tens of attoseconds to 10 nanoseconds.

The proposed activities on APOLLON laser facility will be to extend the capabilities of these sources especially in term of photon energy, duration and total energy.

Indeed, an essential goal of this research topic is to find ways to generate very intense light pulses at short wavelengths (ideally down to the X-ray range), with ultra-short durations down to the attosecond range.

However, this research subject does not only aim at producing new light sources for the benefit of other research fields. It also aims at gaining a fundamental understanding of light-matter interaction in extreme regimes of intensity and duration, the produced radiation being itself an extremely valuable probe of the dynamics of the system.

Three main types of objectives can be identified for this research subject:

- *Fundamental understanding*: studying the basic physical processes involved in high-intensity laser-matter interaction and leading to the generation of short-wavelength radiation.
- *Source properties*: studying the properties of the light sources obtained by these processes.
- *Applications*: using the light sources obtained in this way for novel and original application experiments as single shot X-ray diffraction, highly non-linear processes as multiphotonic processes in the XUV, attosecond dynamics of electrons in matter,…

PLASMA-MIRRORS

A very promising approach to produce ultrashort coherent XUV or X-ray light pulses consists in using reflection of high intensity laser light on a sharp surface. Upon reflection, the non-linear response of this so-called *"plasma-mirror"* induces the generation of high-order harmonics of the incident frequency in the reflected light, associated in the time domain to trains of intense attosecond pulses [Thaury].

The measured conversion efficiencies being extremely significant (up to 10^{-4}), it would be feasible to use this extreme-UV radiation for time-resolved and imaging experiments in chemistry and biology, and also to extend the scope of multiphoton processes in the XUV region. In addition, at higher intensities, the XUV pulse duration is predicted to decrease significantly, giving access to better time resolution in the attosecond domain.

The physics of plasma mirrors, and the main motivations for studying this physics, have been summarized in the 2-year scientific program. Considering the long term objectives on this subject with the APOLLON laser, the broad picture is described hereafter.

Studying the basic physics of high-intensity optics and laser-plasma interaction:

A Plasma mirror is probably the simplest physical system to study the interaction of ultraintense laser fields with a plasma, and can thus be considered as a benchmark to validate theories and models of high-field physics.

In this perspective, the harmonic signal can be considered as a fine in-situ probe of the interaction. It should, for instance, provide information on the influence of the magnetic field or of radiation reaction on the plasma dynamics. This approach would ideally require measuring all possible properties of the harmonic signal, such as the spatial properties (divergence, spatial coherence), the temporal (on the femtosecond and attosecond time scales) or spectral properties in amplitude and phase, and conversion efficiency. Some of these measurements are of course very challenging with a laser such as APOLLON, and simple and innovative methods will have to be found. A good example is photonic streaking using laser wavefront rotation, which can in appropriate conditions resolve the individual attosecond pulses emitted in each cycle of the driving laser pulse, thus providing a temporal picture of the interaction with a resolution of a few femtoseconds [Vincenti].

Manipulating the temporal and spatial properties of intense laser fields:

The second main perspective is to use plasma mirrors to produce new light sources, of potential interest for other experiments. One application that has already been extensively discussed in the literature is the generation of intense attosecond pulses, predicted by numerical simulations (see. Fig.1 and 2). Experiments on APOLLON will have to determine the properties of these pulses: as we have emphasized above, such a characterization is equally important to understand the underlying physics. Experiments will also have to determine the best interaction scheme for this generation: are the pulse properties (e.g. pulse energy) optimized by using bulk targets with tuned density gradients, or optimized bulk densities, or rather thin foils, in transmission or reflection? In connection with the previous point, what are the physical mechanisms involved in the interaction with these different targets? Once this source of attosecond pulses is well-characterized and controlled, it could potentially be used in application experiments, for instance to perform attosecond pump-attosecond probe experiment on the dynamics of electrons in matter. On a laser such as APOLLON, this is of course very challenging and can only be considered as a long term goal.

Plasma mirrors can also be used to manipulate the spatial properties of the reflected light. Spatio-temporal focusing by curved plasma mirror has been proposed as a way to reach extreme light intensities. Even in the absence of a curvature of the initial target, the laser radiation pressure dents the plasma surface, resulting in a natural focusing of the light at a few tens of microns in front on this surface. We will have to find ways to diagnose this focusing and determine the field properties (e.g. intensity) at this point. The key question is: can this focusing be actually used to boost the peak laser intensity, and perform new experiments at unprecedented intensities [Gordienko]? This is for sure a very challenging path, but certainly one that should be investigated with lasers such as APOLLON.

First couple of years of operation of APOLLON

We have briefly described the long-term goals of the study of plasma mirrors with APOLLON. The first experiments with this laser, during the first couple of years of operation, will of course be much less challenging and more consistent with the present state-of-the-art. Initially, they will simply aim at generating a harmonic beam on a simple bulk target (e.g. silica), and measuring its main properties (spectrum, divergence). Besides the interesting physics that is involved in this generation, this will constitute a stringent test of the facility: HHG on plasma mirror is probably one of the most demanding experiments in terms of laser specifications. Indeed:

- Harmonics are only generated if the temporal contrast is high enough, i.e. if ionization of the target does not occur too early before the main pulse.
- The harmonic spectral cut-off is very sensitive to the peak intensity, and hence to the laser beam energy, focusing and temporal compression.
- Finally, the spatial quality of the harmonic (in particular its divergence) is strongly affected by aberrations on the driving laser beam. Phase defects of the laser beam are multiplied by the harmonics order n, and the harmonic beam is thus a sensitive probe of the laser wavefront at focus.

To determine whether or not the experimental results are satisfactory and the laser performances correspond to the specifications, we need to confront the measurements to theoretical predictions. To this end, we have performed 1D and 2D PIC simulations, with laser parameters that correspond to conservative estimates of those expected at the focus of the 10 PW beamline of APOLLON: a peak intensity of 10^{22} W/cm^2, pulse duration of 15 fs. The harmonic spectrum resulting from this interaction is presented in Fig. 3 (red curve), where it is compared to the one obtained when the laser intensity is reduced to 10^{20} W/cm^2 –i.e. the typical regime of present experiments on satellite facilities as UHI100. A considerable increase in generation efficiency is observed at the intensity corresponding to APOLLON. This efficiency reaches a few 10^{-3} for the low-order harmonics (<20), and is still in the 10^{-6} range around the 100th order.

On Fig. 4, we represent the temporal intensity profile of the harmonic field, obtained by filtering the harmonic spectrum generated at I=10^{22} W/cm^2 (blue curve on Fig. 3) for different harmonic orders. We can see that below order 800 (a-b), is the emission consists of a train of attosecond pulses, whereas for orders around 800, a single attosecond pulses is emitted. Beyond these orders, no clear temporal structure is observed in the emission, which can thus be attributed to noise. This has allowed us to define the harmonic cut-off at around harmonic order 800 corresponding to a wavelength as low as 1nm or an energy around 1.2keV.

The second step in the first set of experiments with APOLLON will consist in implementing a simple control of the interaction. We will first control the density gradient scale length at the plasma surface using a prepulse [Rodel], produced with the simple set-up described in the 2-year scientific program. We will then study the interaction with different types of targets, of different densities (from hundreds of n_c for silica, to a few n_c for targets such as aerogels, if possible), as well as HHG on thin foils, either in reflection or transmission. This study will aim at identifying the different interaction regimes and generation mechanisms that are involved.

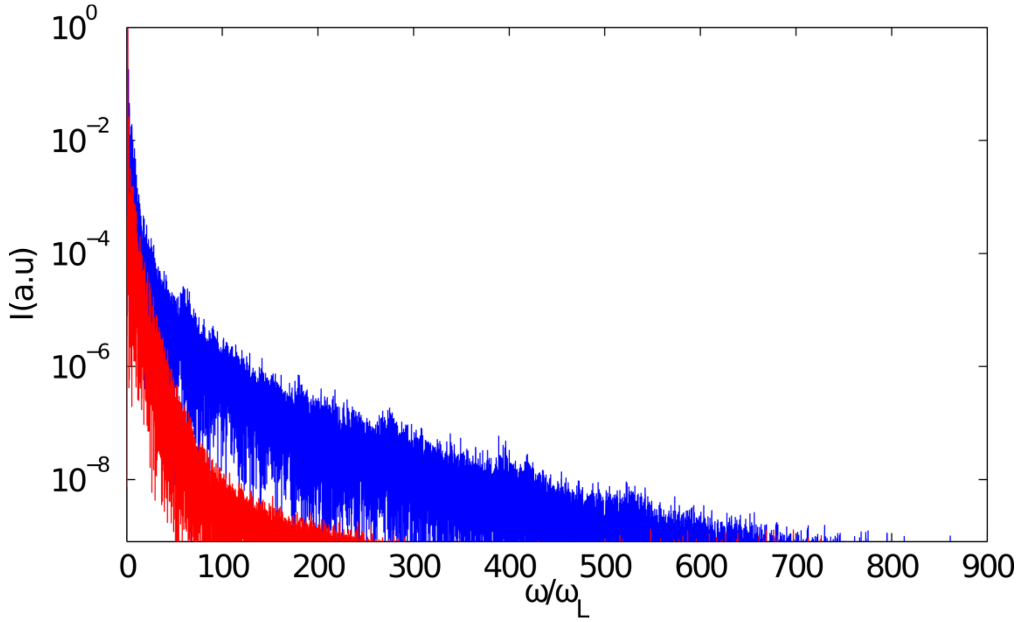

Figure 3 : Harmonic spectra produced on a plasma mirror, as predicted by 1D PIC simulations with EUTERPE, for two different laser intensities, I=1.3 10^{20} W/cm^2 (red curve, present state-of-the–art experiments) and I= 10^{22} W/cm^2 (APOLLON specifications), for a pulse duration of 15 fs (FWHM in intensity), and an initial gradient L=λ/8.

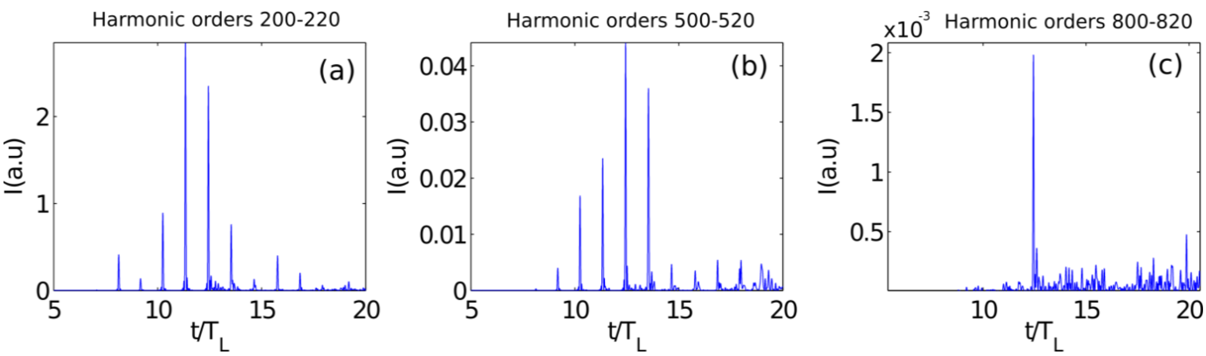

Figure 4: This figure shows the attosecond pulse train reflected field from the plasma mirrors, calculated by filtering the harmonic spectrum generated at I=10^{22} W/cm^2 (blue curve on Fig1) between harmonic orders (a) 200 to 220 (b) 500 to 520 (c) 800 to 820.

In the last step of this first set of experiments, we will start trying to control the plasma dynamics and the HHG emission by tailoring the laser field properties. Two main control schemes will be tested. The first one will consist in using the laser field wavefronts to compensate the effect of the laser-induced curvature of the plasma mirror surface on the harmonic divergence as demonstrated on UHI100 [Vincenti2]. In the second scheme, we will induce temporal wavefront rotation at focus, by a slight rotation of a grating in the compressor, to try to angularly separate the successive attosecond pulses generated on the target [Wheeler]. Achieving this separation would not only produce a remarkable attosecond light source for future experiments, but also provide temporally-resolved information on the dynamics of the plasma.

The following experiments that will be performed on plasma mirrors with APOLLON will be largely determined by the results of these first set of experiments.

XRAY LASERS

Progressing along this long X-Ray lasers road in CILEX is governed by the fact that developing an accurate, high performances plasma-based soft x-ray laser requires pumped laser with energy ranging from few Joules up to 100 Joules, depending on the scheme (see below). APOLLON delivering up to 300 J (before compression) has enough energy to drive such a laser in parallel with other secondary sources from THz to γ-ray or accelerated electron, proton, ions. This is a unique opportunity for developing original pump-probe experiments.
In addition, the LASERIX satellite facility, a unique installation mainly dedicated to the delivering of X-ray sources for users, is the ideal tool to develop the basic physical schemes described hereafter before implementation on APOLLLON-10P.

X-ray laser future trends: shorter wavelengths, brighter beams, shorter durations!

Reaching much shorter wavelengths

Three strategies are currently identified for reaching much shorter wavelengths.

-The simplest, on-line with current development, consists in pushing the limit of the so-called collisional scheme [see Daido for a review]. This pumping scheme is currently the only one that has demonstrated the saturation for laser-created plasma. However, experiments so far are limited by the available pump energy. Typically, with the energy that will be delivered by APOLLON (about 250 J uncompressed and 50 compressed), one may reasonably expect reaching the “water window” i.e. obtain saturated amplification near or below 4 nm.

-The second approach that was recently granted by ANR is using the recombination scheme [Daido]. French teams have long tradition of studying this scheme [Jaegle, Chenais, Hulin]. The technique consists in ionizing the plasma one ionization degree higher than the lasing degree. During the cooling phase, the plasma recombines in populating preferentially the ionic states of higher principal numbers and angular moments, leading to population inversion. For a given pump energy, recombination scheme reaches much shorter wavelengths than collisional scheme [Tallents]. Also, it allows reaching sub-nm wavelengths when collisional scheme is limited to about 3 nm. Recombination scheme requiring the cooling period to be as fast as possible, it would take benefit of using APOLLON that combines femtosecond and energetic pulses. We will either study the recombination scheme for solid and gas targets.

-This third type of photo-pumped soft X-ray lasers will allow extending soft-x-ray lasers to the keV, femtosecond domain. It consists in photo-pumping an atomic gas to induce population inversion by creating holes in inner-shells. This scheme has been very recently demonstrated with LCLS free-electron laser as the source of X-ray photopump (see Fig 5). Lasing emission has been observed at 849 eV [Rohringer]. Experiments done in Salle-Jaune satellite facility using betatron emission to photo-pump the gas target [Ribière] were un-conclusive. This is because 2J per pulse is a bit short to produce a sufficiently high betatron flux. We expect the APOLLON energy high enough to demonstrate such an effect using an IR laser.

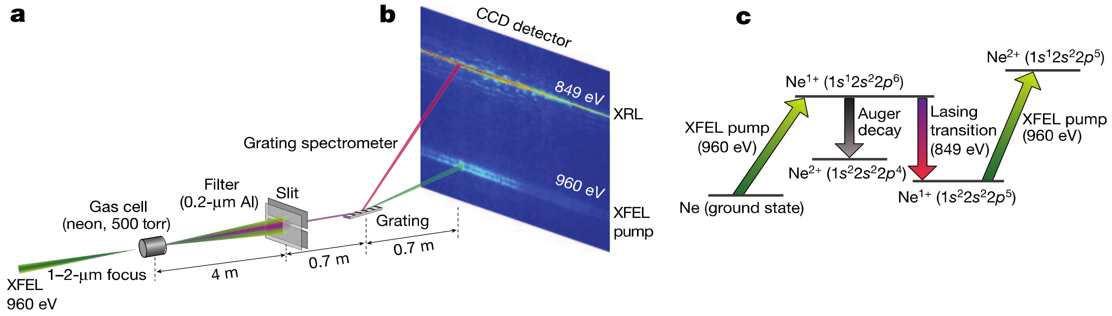

Fig.5 : Experimental scheme. a, The XFEL beam is focused into a gas cell filled with neon to a focus spot of radius 1–2 ***μ****m. A flat-field X-ray grating spectrometer was positioned***,** *4m away from the interaction region. b, The charge coupled-device (CCD) image of the transmitted XFEL pump (bottom) and the XRL (top). c, Level scheme. Population inversion of the* $1s^1 2s^2 2p^6$*-to-*$1s^2 2s^2 2p^5$ *transition is created by K-shell photo-ionization of neutral neon. The Auger decay time of the inverted state (2.4 fs) dominates the kinetics of the system in the small-signal-gain regime. The lower lasing state is depleted by K-shell photo-ionization. (from [Rohringer])*

Reaching intensities comparable to free-electron lasers

Currently two sources are driving the ultra-intense soft x-ray community: free-electron lasers and high-harmonic-generation generated from gases. This last source has unique capacity of producing attosecond pulses that we do not expect to reach with plasma-based soft x-ray laser. However, increasing the energy above 1 µJ per pulse remains a very difficult bottleneck. This is even more complex when considering sub-30 nm wavelengths. Soft X-ray laser demonstrated to-date the highest energy per pulse with 10 mJ. However, this experiment being based on Amplification of Spontaneous Emission (ASE) mode amplified a stochastic noise, generates very energetic but poorly coherent beams. Seeding laser-created plasmas with harmonics allowed generating fully coherent and polarized beams but with energy not exceeding 1 µJ [Zeitoun]. On LASERIX satellite facility, will be developed a complete strategy to move from the current 1 µJ up to several mJ, by using two-stage amplification [Oliva1, Oliva2] (20 µJ, 80 fs expected from modeling) or by using a transposition of CPA to x-rays [Oliva3] (5 mJ, 200 fs). The most successful scheme could be implemented on APOLLON for reaching very high energy.

Breaking the picosecond barrier: down to the 10's fs regime

Pulse duration is at the moment limited to 1 ps for both ASE and seeded soft x-ray lasers. The reasons are different. For ASE, the plasma hydrodynamic governed the pulse duration. For seeded soft x-ray laser, it has been demonstrated that plasma characteristic time, given by the electron-ion collision, is too long (few ps) to accommodate the necessary bandwidth for the amplification of fs

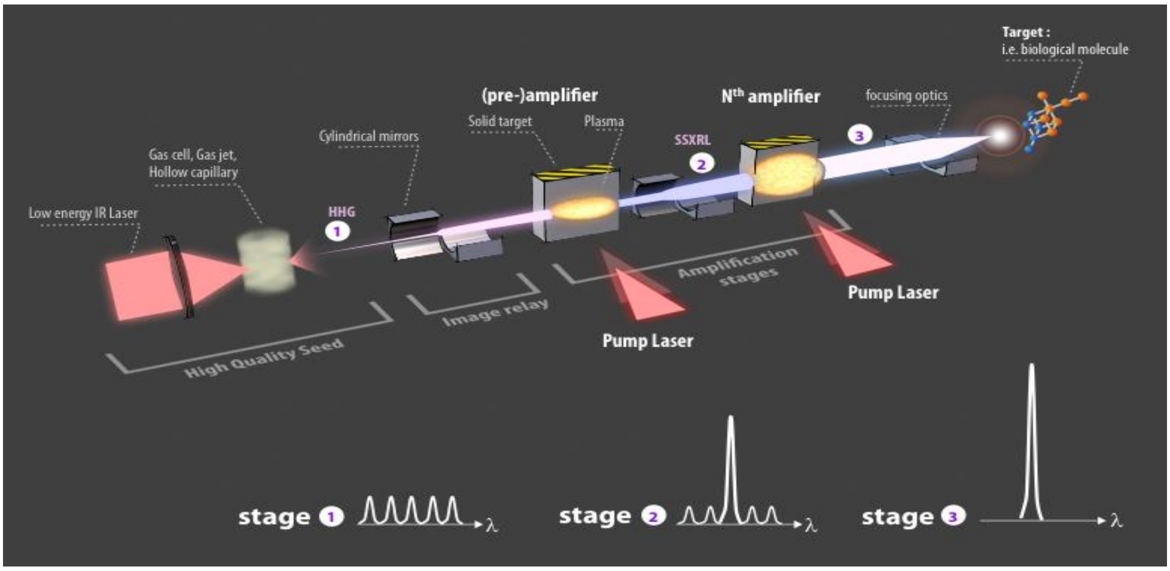

Fig. 6 : Artistic representation of the multi-stage soft x-ray laser, seeded by high harmonic beam.

seeds (high-harmonic). It is has been proposed to increase the density, and thus the electron-ion collision rate, by shaping the plasma [Cassou]. In that case, seeding a high-harmonic with 200 fs duration instead of 20 fs commonly used, allows resonant amplification leading to 80 fs pulse at the plasma exit (compression by saturation) [Oliva1]. It is worth noting that soft x-ray lasers based on high-Z elements like Tantalum have intrinsic larger bandwidths than those using low Z, like iron or molybdenum currently used, opening the route to 10's fs pulse duration. Dedicated modelings are under progress in collaboration between CILEX teams and Universidad Politecnica de Madrid. Preliminary laser parameters are: energy 150 J in uncompressed pulse (~52×10^{14} Wcm^{-2}), 50 J in a pulse compressed down to 1-5 ps ($2\text{-}5\times10^{16}$ Wcm^{-2}). The focal length will be typically few mm long and 100 µm wide. It might be interesting to frequency-double both pulses for shifting the gain region to higher densities. Considering current developments on high harmonic generation in CILEX-satellite facilities we already dispose of intense seeding pulse at 200 eV and we may foresee rapid progress towards 400 eV for seeding Tantalum.

BETATRON RADIATION

Producing a radiation source that simultaneously combines, compactness, high brightness, femtosecond duration, tunability over the entire X-ray spectrum, and micrometer source size, is a major challenge in X-ray science. Such a source would satisfy the need of a wide variety of applications, and could bring, into a university scale laboratory, a powerful tool to explore the properties of matter. For example, femtosecond X-rays, fully synchronized with laser pulses, can reveal the fastest transient atomic or molecular dynamics. Micrometer source size would provide an unprecedented increase of the space resolution to bring into light structural details in materials for broad applications. High energy X-ray radiation, in the few hundreds keV range, will allow to radiograph objects opaque for standard X-ray sources.

Betatron radiation produced by laser plasma interaction is a promising candidate to achieve this goal. Produced at the interaction of an intense laser with a gas jet, the betatron radiation is a moving charged particle radiation emitted by relativistic electrons in a plasma accelerator [Corde]. Here the plasma accelerating structure is an ion cavity formed in the wake of an intense laser pulse that traps, accelerates to relativistic energies and wiggles, a femtosecond electron bunch. The consequence of the electron motion is the emission of a collimated femtosecond X-ray pulse. The mechanism reproduces, in a millimeter scale plasma, the principle of a synchrotron where the couple accelerator and insertion device of a synchrotron is replaced by the ion cavity. This source, combining collimation, X-ray range and femtosecond duration, has been demonstrated for the first time on salle-jaune in 2004 [Rousse1]. Produced using tens TW class lasers, the radiation spectrum extends up to few tens keV, is collimated within a few mrad, has a micrometer source size and a femtosecond duration [Taphuoc].

Betatron X-ray radiation has interesting properties for application experiments: high peak spectral brightness, ultra-short duration, very small source size, as well as femtosecond time-scale synchronization in pump-probe experiments. The potential of betatron radiation was demonstrated with the example of single shot phase contrast imaging of biological samples, where the experiment takes advantage of the very small source size and high spatial coherence of the X-ray beam. For an X-ray source size of 1-2 microns, the coherence length at 1 m from the source is 10 microns, which allows performing phase contrast imaging with a compact setup [Fourmaux].

Betatron X-ray radiation is also a powerful tool to study laser-plasma accelerator physics and for noninvasive measurement of these properties. A novel method has shown the possibility to measure the longitudinal profile of the X-ray emission region, giving insight into the history of the laser-plasma interaction. Finally, Betatron radiation was used for femtosecond X-ray diffraction and X-ray absorption experiments [Corde2].

Since 2004, numerous studies have been done using 100 TW-class lasers at LOA and worldwide. The LOA team has in particular provided a full characterization of the source and a deep understanding of the related physics as well as the first applications in ultrafast X-ray science and high resolution imaging. However, the energy of the Betatron radiation must be increased to satisfy the need of a larger number of applications. This will be possible using the PW class APOLLON laser. At this high laser power, laser plasma accelerators will produce electron in the GeV range. As shown on figure 7, using these electrons, it is expected to produce Betatron radiation in the few hundreds keV range. The spectrum will depend on the electron energy and with existing injection and acceleration methods it will be possible to control the spectrum of the radiation [Rousse2]. We expect to produce X-ray beams up to about 500 keV, collimated within a few mrad and containing up to 10^{10} photons/shot. At this energy and intensity, Betatron radiation will be a unique tool for applications as, for example, nondestructive testing with a micrometer resolution and high energy femtosecond diffraction.

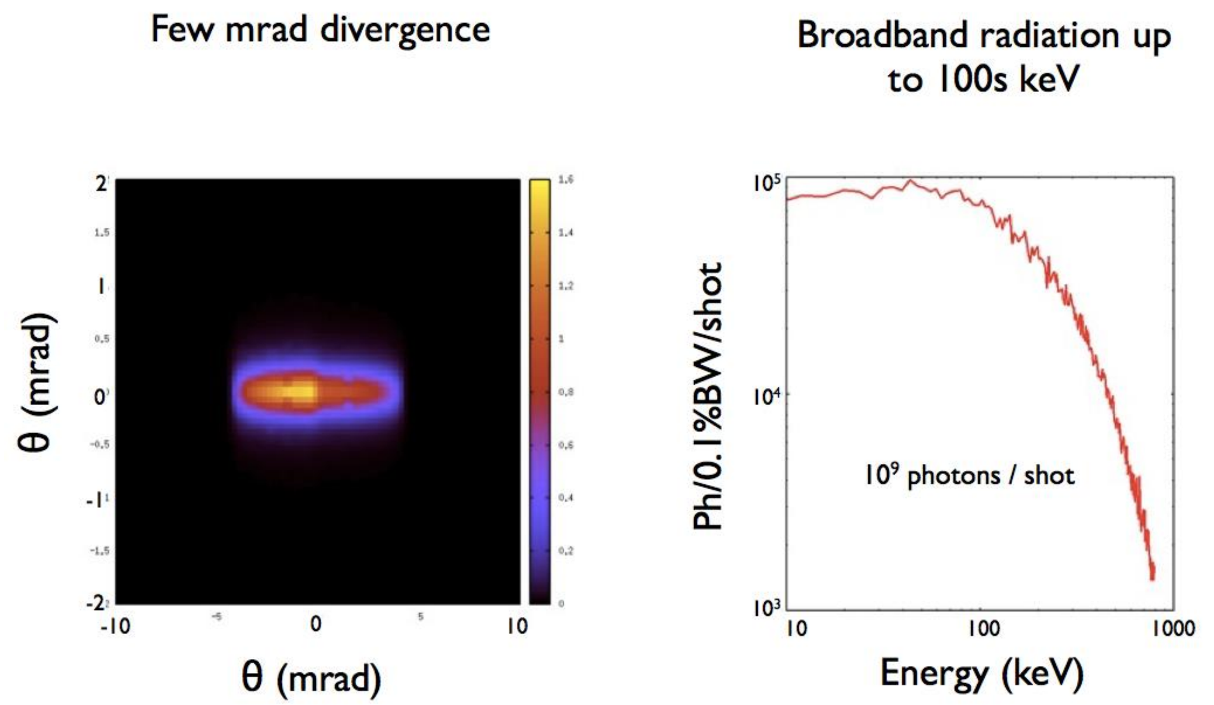

Figure 7 : Betatron radiation beam expected from the acceleration of 2GeV and 100nC electron beam in laser-produced plasmas.

FLYING MIRRORS

Laser-accelerated particles can produce relativistic “flying-mirrors”, which can be used to frequency-up-shift in the X-ray domain and temporally compress intense laser pulses to attosecond domains [Kando]. When a relativistic short pulse propagates in underdense plasmas, it can generate a wake. Near the wave-breaking threshold, the electron density in this wake exhibits sharp spikes. These spikes move at a phase velocity equal to the group velocity of the driver pulse, which is close to the velocity of light in vacuum. If one sends a second beam in the opposite direction, it will be reflected back from what is known as the relativistic flying mirror, which is nothing but a double Doppler shift. The reflected pulse will present a much higher frequency ($4\gamma^2$) and a much shorter duration.

This experiment could also be done using a thin solid target which will generate, after focusing high contrast pulse on the surface, a sheath of free electrons which will be used as relativistic reflector for the second counter propagative beam whose frequency will be $4\gamma^2$ up-shifted through the Doppler effect.

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HIGH-FIELD PHYSICS

The tightly focused multi-PW laser pulse of APOLLON will allow entering deeply in the ultra-relativistic regime of laser-plasma interaction where the so-called classical nonlinearity parameter $a_0 = E_L/E_C$ strongly exceed 1. Here E_L is the laser electric field amplitude, and $E_C = m_e\, c\, \omega_0/e$ is the so-called Compton field above which an electron gain a relativistic energy in less than a laser optical cycle (e and m_e are the electron charge and mass respectively, c is the light velocity and ω_0 is the laser frequency). In this regime, electrons are strongly and suddenly accelerated and/or decelerated. They radiate away a significant part of their energy emitting γ photons and exchanging momentum with the electromagnetic field. This process, accompanied by the absorption/scattering of many laser photons, is called nonlinear Thomson or nonlinear Compton scattering, depending on whether quantum effects are negligible or not.

The importance of purely-quantum effects on an electron is controlled by the so-called quantum nonlinearity parameter $\chi_0 = (\varepsilon/c - p_{/\!/})/(mc)\ E_L/E_S$, which depends on both the electron energy ε and longitudinal momentum $p_{/\!/}$, and the laser field amplitude E_L. This parameter measures, in the frame moving with the electron, the ratio of the electric field seen by the electron to the critical field of quantum-electrodynamics $E_S = m_e^2c^3/(e\hbar) = 1.3\ 10^{16}$ V/cm and $\hbar$ is the Planck constant. This critical field, also referred to as Schwinger field, corresponds to the field strength required to accelerate an electron to relativistic velocities on a distance corresponding to the Compton electron wavelength $\lambda c = h/mc = 0.023$A°. For $\chi_0 \sim 1$, pure quantum effects such as the electron recoil due to the emission of particularly energetic photons or electron-pair creation start to kick-in.

The copious emission of high-energy photons and its back-reaction on the electron dynamics (and in turns on the whole laser-plasma interaction) will not only be interesting in terms of potential applications (e.g. for high-energy photon and particle sources) but also for our fundamental understanding of laser-matter interaction in a regime where the breakout of classical electrodynamics (CED) is expected, and a bridge between ultra-relativistic plasma physics and quantum electrodynamics (QED) has to be made.

HIGH ENERGY PHOTON EMISSION AND ITS BACK-REACTION IN LASER-PLASMA INTERACTION

Laser-plasma interaction in the multi-PW regime appears as a promising path toward a new ultra-bright and ultra-short source of high-energy photons. PIC simulations indeed indicate that up to 40 % of the laser energy can be converted in γ photons with the energy in the range of a few MeV to a few tens of MeV [Grech, Ridgers]. In particular, efficient conversion from the laser energy to the high-energy photon can be achieved in the so-called relativistic-self-induced transparency regime. The possibility to diagnose such emission on the APOLLON laser facility would be most appealing for future applications. In addition, emission of high-energy photons may strongly modify the overall laser-plasma interaction and its careful investigation has important fundamental motivations.

Indeed, the dynamics of a radiating electron in an external field is not fully captured by the Lorentz equation of motion. In the realm of CED, an additional - so-called radiation reaction - force has to be considered to account for the electron's loss of momentum due to the emission of high-energy photons. In the absence of any quantum effects ($\chi_0 << 1$), this force can be described by the Landau and Lifschitz (LL) formula. This force acts, in a first approximation for ultra-relativistic particles, as a friction force with both non-linear and non-isotropic coefficient [Landau].

As shown on figures 8 and 9, recent studies using PIC simulations have demonstrated that, for laser intensities beyond 10^{22} W/cm^2, this radiation force is strong enough to modify the electron motion, and in turn the ion dynamics during laser-plasma interaction with significant effects on electron heating [Tamburini1,Grech], ion acceleration [Tamburini2] or high-energy photon emission [Grech]. Investigation of the signature of radiation-reaction effects in laser-plasma experiments would be particularly interesting as the LL formula for the radiation reaction force still lacks strong experimental support in the extreme fields generated by ultra-intense laser beams (usually in accelerators, the regime is quite different: one has a small Radiation Reaction (RR) force but for a relatively long time, such that RR effects accumulate. Here we would like to test the LL equation, when a great loss of energy occurs in a single laser optical period).

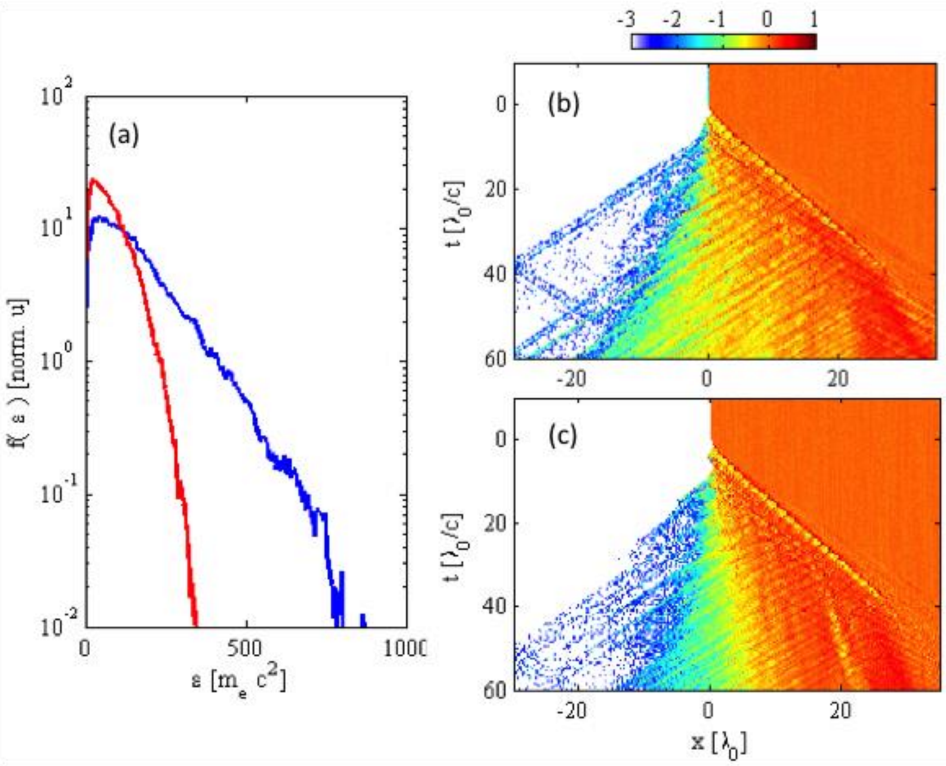

Fig. 8: Results from PIC simulations: a linearly polarized laser pulse with intensity 8 10^{22} W/cm^2 is focused on a semi-infinite plasma with density 10 n_c. (a) Electron energy distribution at the end of the simulation with (red) and without (blue) accounting for radiation reaction. (b,c) Temporal evolution of the electron density without radiation reaction (b) and with radiation reaction (c). Simulations performed with the 1d3v PIC code SQUASH [Grech].

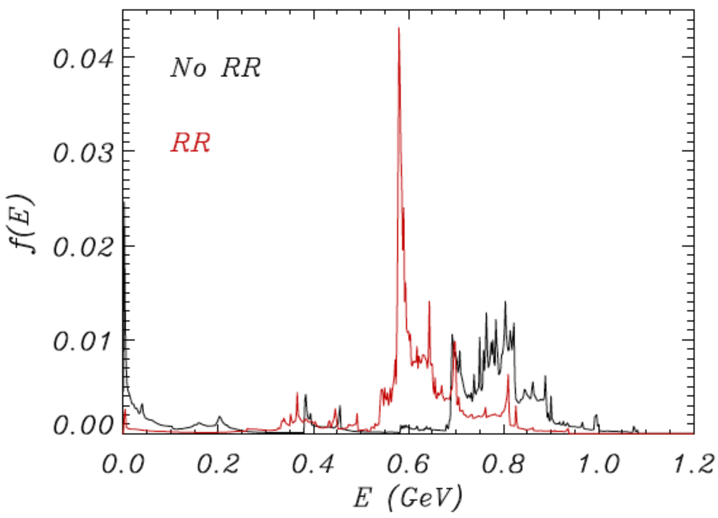

Fig. 9: Ion energy spectra during the radiation pressure acceleration of a thin (micrometric) foil by a linearly polarized laser pulse at 2 10^{23} W/cm^2. Results from PIC simulations [Tamburini2].

Recent studies using PIC simulations have demonstrated that, for laser intensities beyond 10^{22} W/cm^2, this radiation force is strong enough to modify the electron motion, and in turn the ion dynamics during laser-plasma interaction with significant effects on electron heating [Tamburini1,Grech], ion acceleration [Tamburini2] or high-energy photon emission [Grech]. Investigation of the signature of radiation-reaction effects in laser-plasma experiments would be particularly interesting as the LL formula for the radiation reaction force still lacks strong experimental support in the extreme fields generated by ultra-intense laser beams (usually in accelerators, the regime is quite different: one has a small Radiation Reaction (RR) force but for a relatively long time, such that RR effects accumulate. Here we would like to test the LL equation, when a great loss of energy occurs in a single laser optical period).

Furthermore, when the quantum-parameter χ_0 becomes of the order of or larger than unity, pure quantum effects have to be accounted for. In particular, the electron can now emit some particularly energetic photons which will take away most of its energy at once. This process, often referred to as photon recoil, results in a straggling effect as the electron trajectory becomes discontinuous. Obviously, such trajectories cannot be modeled using a friction force. While, in the classical regime, radiation reaction followed from the incoherent emission of many energetic photons, each emission smoothly modifying the electron motion, quantum effects allow for very discontinuous electron trajectories which modeling requires the use of Monte-Carlo methods.

High-energy photon emission and its back-reaction will be investigated in laser-plasma interaction by carefully studying the properties of the resulting high-energy photons, electrons and ions. It should be stressed however that if it is possible to “turn-off” back-reaction in numerical simulations to “measure” its effects, this is not the case in the experiments. Furthermore, these properties strongly depend on the overall laser-plasma interaction, making it difficult to distinguish pure RR effects from other processes. A more convenient way to study radiation-reaction may be provided by considering electron beam scattering by the intense APOLLON laser. This approach is investigated in the following Section.

Non-linear Compton / Thomson Scattering from laser-created electron beams

High-energy electron beams can be created in situ using the APOLLON laser, which provides us with the unique opportunity to study radiation reaction in a controlled way using an all-optical set-up. Different proposals have been put forward aiming at testing the various models for the radiation reaction force. In particular, the existence of a regime, known as classical radiation dominated regime, has been demonstrated theoretically where an electron loses an energy of the order of its initial energy in a single laser optical cycle so that the electron dynamics is strongly affected by RR. In [Koga] it is suggested that this regime can be achieved experimentally by employing a laser with intensity 10^{23} W/cm^2.

In [DiPiazza3] a different regime has been investigated, which is parametrically less demanding than the classical radiation dominated regime but in which the effects of RR are still large. It is shown that the apex angle of the angular distribution of the emitted radiation, with and without RR effects included, may differ by more than 10 degrees at laser intensity of 5×10^{22} W/cm^2 by considering initial electron energy of 40 MeV. The effects of RR on the final energy distribution of an electron beam passing through a laser beam have been investigated in [Thomas]. It has been shown that an electron beam with average energy of 800 MeV head-on colliding with a strong laser field of intensity 10^{22}W/cm^2 loses almost half of its energy due to RR. Furthermore, this set-up will allow us to investigate nonlinear Thomson and Compton scattering in regimes never achieved before.

The first experiment on non-linear Compton scattering was performed at the Stanford Linear Accelerator Center (SLAC) [Bula] in 1996. In this experiment, an ultra-relativistic electron beam with energy of ~46 GeV collided with a TW Nd: glass laser with an intensity of 10^{18}W/cm^2. Correspondingly, the quantum nonlinearity was χ_0=0.25. This experiment thus took place in a regime of weak quantum (χ_0<1) nonlinearity but a four-photon absorption process has been observed for the first time on a free relativistic electron.

The APOLLON laser facility will make it possible to investigate non-linear Compton scattering in very nonlinear and quantum regimes by considering an all-optical set-up where a quasi-counter propagative ultra-relativistic electron beam produced by wake field acceleration collides with a multi-PW laser beam. In particular, the extreme electron energies and laser intensities available at the APOLLON facility will allow us to probe the regimes where the quantum parameter ranges from χ_0=1 to 20.

To highlight the characteristic laser-electron interaction in these regimes, we present here some purely quantum calculations [Dipiazza]. They are based on the S matrix formalism where the spinor wave functions of the electron in the presence of the laser field are obtained by solving the Dirac equation for a free particle [Volkov].

We have calculated both the electron and radiated spectra considering the realistic parameters given in the above table for the laser intensity and the electron beam energy (the laser pulse duration is 15fs).

Intensity (W/cm^2)	Energy (GeV)	χ_0	spectra
10^{18}	46	0.25	SLAC
10^{22}	1	0.60	1
10^{22}	10	6	2
10^{23}	1	2	3
10^{23}	10	20	4

First, because these conditions will be probably close to the first conditions we will get on APOLLON, we have considered 10^{22} W/cm^2 and a 1 GeV electron beam produced by wake-field.

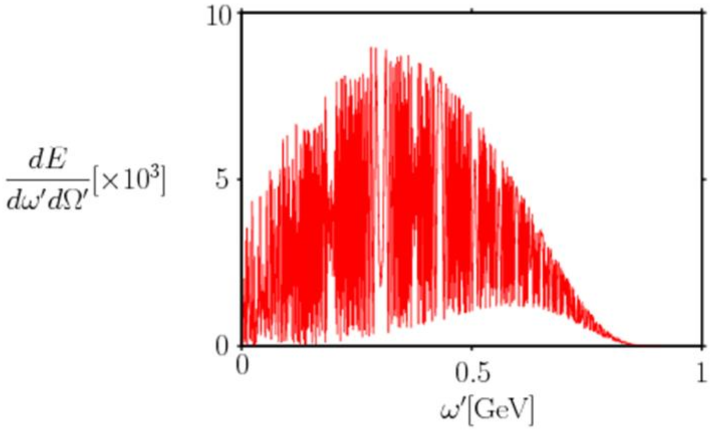

Figure 10: Energy emission spectrum for 10^{22} W/cm^2 and an electron with initial energy of 1 GeV at the emission angle 178°

The resulting emission spectrum with such numerical parameters is shown in Fig 10, by considering a single electron and by including only the emission of a single photon. The spectrum shows the typical quantum pile up of the radiation up to the maximal allowed frequency, which in this case is about 1 GeV [Mackenroth]. Since the nonlinear quantum parameter is equal to 0.6, quantum effects start to come into play. A plot of the emission spectrum via the classical approach would show "unphysical" emission of photons at energies much higher than 1 GeV. We have also to point out that for the above-mentioned numerical parameters; the average number of photons emitted by an electron is about 8.

Total photon energy spectrum are shown in Fig. 11 a,b,c, by employing a kinetic approach [Neitz], which automatically includes the emission of many photons, which in turn corresponds to radiation reaction in the quantum regime [Dipiazza2]. According to the above table, these results have been obtained by considering an initial electron with a Gaussian energy distribution centered at 1 GeV and 10 GeV and with an energy width of 10%, as for laser wakefield produced beams [Esarey]. We present also the electron spectra after the interaction in Fig 12 a,b,c in the forward direction and integrated over space. Note that, the electrons beams have lost a substantial quantity of energy corresponding to the photon energy gains.

The spectrum shows the typical quantum pile up of the radiation up to the maximal allowed frequency, which in this case is about 1 GeV and 10 GeV.

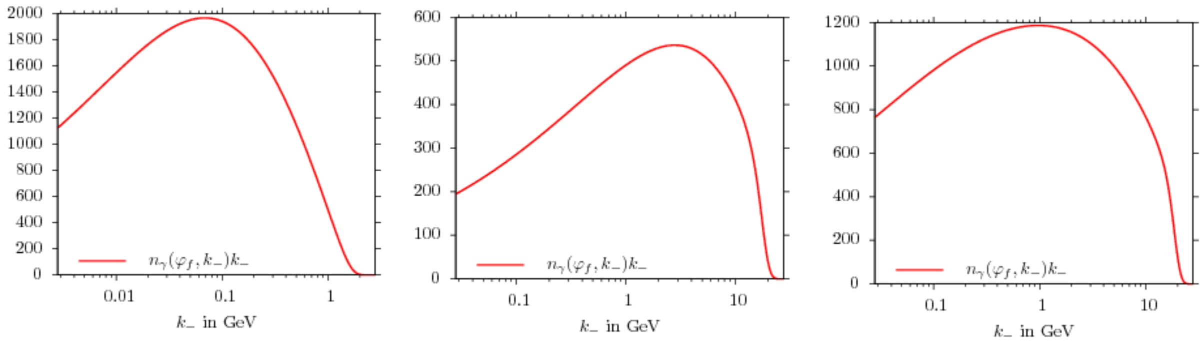

Figure 11 a,b,c : non-linear Compton spectra for conditions 1,2 and 3 of the table 1.

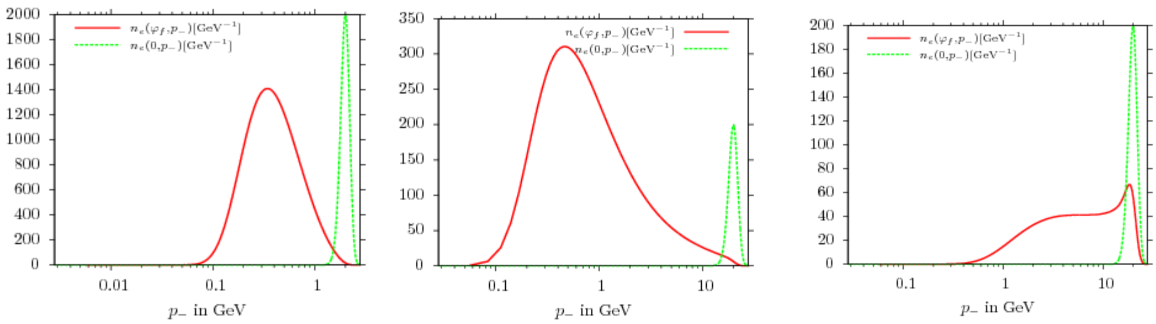

Figure 12 a,b,c : Electron spectra for conditions 1,2 and 3 of the table 1.In green forward emission, in red, integrated spectra.

By comparing Fig. 11 with Fig. 12a, we note that the main effect of multiple photon emission is that the peak of the maximum emission is shifted to much lower energy values, as already predicted in [Dipiazza2] where it was established that the effect of multiple photon emission is the quantum equivalent of radiation reaction (RR) in CED at moderate values of the nonlinear quantum parameter (note that $k_- \approx 2\omega'$). In this way, APOLLON can be a unique tool to understand the quantum origin of RR, which has to be still fully investigated.

Pair production in the presence of strong Coulomb fields

The copious emission of highly energetic photons and the presence of ultra-relativistic electrons are propitious for the production of electron-positron pairs. Pair creation may follow from the collision of energetic electrons with highly charged ions via the Trident and/or Bethe-Heitler mechanisms. The Trident mechanism corresponds to the creation of an electron-positron pair during the direct collision of an energetic electron with the Coulomb field of a high-Z ion [Babbha]. The Bethe-Heitler two-step process: first an electron deflected in the field of a highly-charged ion emits a Bremsstrahlung photon. If this photon energy exceeds 1.022 MeV (twice the mass of an electron or a positron), it can decay in an electron-positron pair when interacting with the Coulomb field of another ion [Heitler]. While these mechanisms have been known and studied for years, little is known about pair creation/annihilation in a plasma environment. Their modeling in PIC simulation remains at its beginning even though experimental evidences of both mechanisms have recently been given. Indeed, up to 10^{10} positrons/steradian, with energy up to 20 MeV, have been obtained at the Lawrence Livermore National Laboratory [Chen] by focusing a picosecond laser pulse at 10^{20}

W/cm^2 onto a mm thick gold target and first measurements of the emittance has been made [Chen2] demonstrating an emittance comparable with existing accelerators.

Pair production by direct interaction between ultra-relativistic electrons and the incident laser field may also arise for laser intensities exceeding 10^{23} W/cm^2. In this scenario, electron-positron pairs are created by the multi-photon Breit-Wheeler: high-energy ($> 2\ m_ec^2$) photons created by nonlinear Compton scattering interact with many laser photons and decay in an electron-positron pair.

PIC simulations of a 10 PW laser pulse striking a 1 micron Aluminium target have recently been presented [Ridgers]. These simulations include a Monte-Carlo routine to treat both high-energy photon and pair creation, and have demonstrated that (i) up to 35% of the laser energy can be converted to high-energy γ-radiation, and that (ii) up to 10^{10} electron-positron pairs can be created. Interestingly, not only positrons are created, they are also accelerated in the strong self-consistent fields developing during the laser-plasma interaction. Indeed, the resulting average positron energy is of the order of 250 MeV, which is much larger than the energy of the photons from which they originate.
Such creations of intense, energetic positrons in the laboratory will not only offer new opportunities for applications or fundamental physics, from antimatter research to astrophysics; it is also a unique opportunity to make a bridge between plasma physics and quantum electrodynamics.

ELECTRON ACCELERATION FROM VACUUM : A POSSIBILITY TO MEASURE THE LASER INTENSITY ?

In this section we describe a recently proposed method [Har-Shemesh] which could help determining the peak intensity of strong laser pulses in the range between 10^{20} W/cm^2 and 10^{23} W/cm^2, a very hard (and famous !) experimental difficulty. The method exploits the highly directional nature of the emission of radiation by an ultra-relativistic, accelerated charged particle. By assuming that in the ultra-relativistic limit the electron emits electromagnetic radiation entirely along its instantaneous velocity, we relate the aperture of the electron's radiation pattern to the peak intensity of the laser pulse.

In our setup, an electron beam collides head-on with a strong laser pulse and the aim is to determine the peak intensity of the pulse. From the analytical solution of the motion of an electron in a plane wave, we learn that the electron stays relativistic throughout its motion within the laser pulse if it is initially relativistic and that the motion is confined to the plane determined by the laser polarization and the laser propagation direction. The maximum angle θ_m between the velocity vector and the initial propagation direction is related to the relativistic parameter $\boldsymbol{\xi}_0$ and to the initial Lorentz factor γ_0 of the electron by the relation $\boldsymbol{\xi}_0=2\gamma_0\sin(\theta_m)/[1+\cos(\theta_m)]$. Thus, the peak intensity I_p of the laser field is related to θ_m via the relation $I_p[10^{20}\ W/cm^2]=0.28\{\omega_0[eV]\varepsilon_0[MeV]\sin(\theta_m)/[1+\cos(\theta_m)]\}^2$, where ω_0 and ε_0 are the laser photon energy and the initial electron energy, respectively. As we have mentioned, radiation-reaction effects may alter the electron dynamics at such high intensities. In this case the equation of motion of the electron is the LL and it is not possible to determine analytically the relation between the laser peak intensity and the radiation aperture angle θ_m. However, this is still possible numerically (see the original paper [Har-Shemesh] for details).

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