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Investigating strong-field QED processes in laser-electron beam collisions at Apollon

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Abstract - A new class of high-power lasers is emerging that will soon allow for the realisation of pioneering experiments in the field of extreme light laser-matter interaction, where relativistic laser-plasma physics is strongly impacted by quantum electrodynamics (QED) effects. Experiments are being designed that will be performed at the Apollon research infrastructure (RI) [1-3], a multi-beam multi-PW facility on the *Plateau de Saclay*, 20 km south of Paris. Such a facility represents an exceptional environment for the scientific community to study the collision of a laser-driven multi-GeV electron beam with a multi-petawatt (up to 10 PW), ultra-intense ($\geq 10^{23}$ W/cm²), ultra-short (15 - 20 fs) light pulse. This experimental approach is indeed of utmost importance for the emerging field of extreme light physics. It provides the shortest, all-optical path to unlock a yet largely unexplored regime of laser-matter interaction, and will ultimately make it possible to develop novel ultra-bright sources of high-energy (from 10s of MeV up to several GeV) γ -photons and high-charge beams (from 100 pC to few nC) ultra-relativistic electron-positron pairs. Completing this experimental objective, however, will necessitate substantial developments in terms of particle and photon diagnostics and high-performance computing (HPC), together with advances in the understanding of the physical processes at play. Beyond the possibility to create new sources of light and particles, such work can also open new opportunities in terms of fundamental science [4].

Scientific goal

Studying the interaction of ultra-relativistic electron beams with multi-PW laser pulses opens one of the most promising avenues to the new regime of extreme light physics. As the Apollon RI offers multiple high-power (PW to multi-PW) laser beam capabilities, see Sec. *Required Tools* for details, it provides the scientific community with all the required tools to investigate strong-field QED processes in laser-electron beam collisions.

The flagship experiment envisioned in this project was investigated *in silico*, in a recent work by partners of this project [5]. This work presented the first fully integrated numerical simulation of what such an experiment would ultimately lead to, if performed on the Apollon facility. In this numerical experiment, the F2 (1PW) beam of the Apollon RI is used to drive an electron beam with nC charge and a few GeV energy (60% of the total beam charges have an energy in between 2.5 and 3.8 GeV). This beam is then collided with a 5PW, 15 fs light pulse focused to a peak intensity $I_0 \sim 10^{23}$ W/cm², as accessible with the main Apollon beam F1. This on-chip experiment led to two remarkable predictions. First, the electron-light collision produces an ultrafast (~ 10 fs) γ -photon burst, over a broad spectrum of energies: the average photon energy is typically of a few tens of MeV, and goes up to a maximum energy of a few GeV, slightly below the maximum incident electron energy. The reported brilliance of the photon source, of the order of 5×10^{23} photons/s/mm²/mrad² 0.1%BW, is particularly striking, as it is three orders of magnitude larger than the current experimental record in laser-based Compton sources [6]. Second, as this photon burst interacts back with the multi-PW laser pulse, it produces a high energy (average energy of a few 100's MeV and maximum energy of a few GeV), low divergence (< 0.1 rad) electron-positron pair plasma jet with a total charge of a few 100s pC.

The realization of such an experiment at Apollon will require cross-field expertise and the tight collaboration between experts in various fields of research, from laser-plasma interaction to strong-field QED, from designing high-energy particle diagnostics to performing high-fidelity simulations on the latest HPC architectures. With this challenging framework, the achievement of this flagship experiment relies on the progressive fulfilment of three interdependent experimental milestones.

Developing a well-controlled multi-GeV laser wakefield electron source – A first challenge consists in the implementation of a multi-GeV laser wakefield electron source. Accelerating high-quality electron beams in a single stage is a key objective of the project that will require combining laser-guiding and controlled injection techniques for LWFA. Both techniques have never been made to work together on a multi-PW-class laser such as Apollon. Meeting this challenge is however possible by using an innovative technique for laser guiding that has been recently developed at the *Laboratoire d'Optique Appliquée* [7,8] and that is compatible with controlled injection techniques. Electron beams with energies of 8-10 GeV are expected.

Performing experiments on high-energy photon emission and radiation reaction, from the classical to quantum regimes – The dynamics of ultra-relativistic electrons in a relativistically intense ($I_0 \gg 10^{18}$ W/cm², for laser beams with wavelength $\lambda \sim 1\mu\text{m}$) light pulse is highly nonlinear. At very high intensities, electrons are also so strongly accelerated/decelerated that they start emitting very high-energy radiation in the form of γ -photons. Doing so, they lose part of their energy and momentum, and their dynamics is strongly modified, a process known as radiation reaction (RR).

In the classical regime, γ -photon emission by an ultra-relativistic electron can be modeled as incoherent synchrotron emission, also referred to as nonlinear Thomson scattering. In this regime, RR follows from the cumulative effect of many such emissions, each emitted photon carrying away a very small part of the emitting electron energy [4]. It can be modeled as a continuous force acting on the electron which turns out to be the classical RR force predicted by Landau and Lifshitz [9].

As either the laser field strength (corr. intensity) or electron energy increases, so does the characteristic energy of the emitted photons. The energy of a single photon eventually becomes of the order of the energy of the emitting electron. At this stage, the quantum nature of high-energy photon emission and its back-reaction can be only understood in a relativistic and quantum framework, that of QED, and strong-field QED in particular. The quantum nature of the photon emission manifests itself through three effects. (i) The strong electron recoil as it emits a photon carrying away a significant fraction of its energy leads to a cut-off in the radiation spectrum at large photon energies. (ii) A spin contribution to the radiation needs to be included. When both effects are important, one no longer refers to the emission process as nonlinear Thomson scattering, but as Inverse Compton Scattering (ICS). The associated modification in the photon spectrum will be among the experimental signatures searched for when investigating quantum RR in the forthcoming experiments. (iii) The third and most striking effect is the stochastic nature of the photon emission that has a lasting and measurable (broadening) impact on the electron energy distribution [10-13], in particular if the beam initially has an initially narrow energy spread.

There is a strong fundamental interest in performing such experiments. The full experimental characterization of RR in the relativistic regime still eludes us, despite strong efforts in this direction (in the UK using the high-power laser GEMINI [14,15], and at CERN using electron beams in aligned crystals [16], to mention only the most recent works). It should also be noted that, under the extreme conditions envisioned at Apollon, the RR force will be of the same order as the Lorentz force, and its impact on laser-plasma interaction becomes unavoidable. Last, on a more practical side, this kind of experiment is particularly interesting as it naturally gives rise to strong, collimated and ultrafast emissions of γ -photons, potentially leading to the brightest achievable laser-based photon sources.

Probing strong-field QED and electron-positron pair production – The most exotic process and striking demonstration of strong-field QED envisioned at Apollon is electron-positron pair production. This pure-QED process mainly follows from the interaction of a high-energy γ -photon with a strong electromagnetic field. When the interaction of the high-energy γ -photons (produced by ICS during the electron-laser collision) is directly with the strong laser field, the QED process is then referred to as the nonlinear Breit-Wheeler pair process. It was first observed in the seminal E-144 experiment [17], performed at SLAC in the mid-1990's. However, this experiment was performed in a marginally relativistic laser interaction regime and only a few (106 ± 14) positrons

were detected in over 20 000 electron-laser beam collisions. Abundant production of nonlinear Breit-Wheeler pairs on multi-PW-class laser facilities would be an important contribution to the field of extreme light physics, as well as a major experimental achievement with outstanding repercussions in terms of radiation and particle sources. As previously pointed out, the recent numerical experiments by Lobet *et al.* [5] suggests that billions of positrons would be produced together with the brightest γ -ray flash ever produced in a laser-plasma experiment.

Tools required

This experimental study will be performed at the multi-beam, multi-PW Apollon RI, over the next years, at its different development stages. Apollon will feature at full capability 4 independent beams, with a 1shot/min repetition rate. A main 10PW beam (F1) will deliver up to 150J on target, within 15fs (and up to few ps). A second 1PW beam (F2) will deliver 15J in 15 fs (and up to few ps). These two ultra-high intensity beams will be completed by a ns beam (F3) delivering up to 200J, and a probe beam (F4) delivering 0.2J within less than 20fs.

All beams will be delivered to either one of the two radio-protected experimental areas: the Short Focal Area (SFA) and Long Focal Area (LFA). The SFA has been designed for tight-focusing of both F1 and F2 beams, thus allowing for the highest intensities on target. Yet, this area can be ill suited for the study of electron-laser-beam collisions, as envisioned here. In contrast, the LFA, primarily designed for the study of laser-driven electron acceleration, is well adapted to performing experiments with GeV to multi-GeV electron beams, and can be tuned for studying the collision of such a particle beam with an intense light pulse. As of today, commissioning experiments are being performed with the F2 beam, at full energy on target, in both experimental rooms.

In order to fully exploit Apollon IR capabilities and experimentally investigate the physics at play, novel and dedicated particle and photon diagnostics will be developed and implemented to characterize the energy and angular distributions of the particles, leptons or photons, resulting from the electron-laser-beam collisions. Accuracy in the spectral features of both electrons/positrons and photons will be needed to distinguish the signatures of the different regimes of interaction and describe the transition from one to the other. The upgrade of currently available diagnostics and developments of novel ones will meet the strict requirements in terms of sensitivity and robustness in a very noisy environment and work at the high repetition rate of 1 shot/min.

Last, HPC-relevant simulation tools, such as the particle-in-cell codes CALDER [18,19] and SMILEI [20], will continue to be developed to support the design of and help interpreting future experiments.

Scientific impacts

The process leading to the realization of such experiments will require and foster important fundamental studies, the development of simulation codes with the capability to model QED plasmas on the latest supercomputer architectures, as well as the development of new diagnostics for high-energy particle detection and characterization. Important contributions will be made to fundamental science questions related to the study of high-energy photon production and its back-reaction on the electron dynamics, as well as electron-pair production in strong Coulomb or electromagnetic fields.

Beyond these fundamental aspects, the kind of experiments designed and performed at Apollon at the different steps of this experimental program will ultimately lead to the realization of novel, ultra-bright sources of high-energy (from 10's of MeV up to several GeV) γ -photons and highly-charged (from 100 pC to potentially few nC) ultra-relativistic electron-positron pair jets.

Broader impacts

The advent of multi-PW laser facilities will unlock the largely unexplored regime of extreme light laser-matter interaction. It will enable extreme plasma environments to be studied where collective relativistic effects and strong-field QED processes are intrinsically intertwined. It will allow theoretical models as well as new simulation tools to be tested in regimes never achieved before. Such extreme regimes are not only important for the new generation of multi-PW laser facilities, they are also relevant to astrophysical settings such as encountered during the lepton epoch or in the vicinity of the most extreme objects found in the Universe, such as pulsars' magnetospheres and nebulae or gamma-ray bursts.

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