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Editorial

Topical issue on Fundamental physics and ultra-high laser fields

Editorial

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This special issue is dedicated to the investigation of the new physics that has been opened up in the last decade by our recently acquired ability to produce relativistic plasmas in the laboratory [1]. Relativistic plasmas [2] are systems of charged long-range interacting particles in which either their disordered (thermal) kinetic energy or their ordered (fluid) kinetic energy is at least as large as the rest mass energy of the lighter particles (the electrons in general).

Relativistic plasmas are a fundamental part of our universe [3] but have not been generated routinely in the laboratory until recently. For some time charged particles have been brought to relativistic energies in the laboratory using particle accelerators but the novel feature that characterizes relativistic plasmas in contrast to bunches of accelerated particles is that their dynamics is not determined almost completely by externally imposed electromagnetic fields, the intraparticle interaction being at most a perturbing effect, but is largely controlled by the self-consistent electromagnetic fields generated by the very particles in the plasma. At the same time, for the plasma densities and energies of interest in dilute, high-energy laboratory plasma experiments, the fine scale structure of the interaction between particles can generally be disregarded and a mean field approximation can be adopted in describing the collective plasma dynamics. In such a mean field plasma description the sources of the electromagnetic fields are given in terms of smooth particle distributions in phase space [4].

The selfconsistent electromagnetic interaction makes the plasma respond nonlinearly to perturbations and the Hamiltonian nature of the mean field approximation expresses the fact that, in general, thermodynamic equilibrium conditions inside the plasma are not reached on the dynamical time scales of interest. This leads to a complex plasma behaviour where a bewildering range of collective instabilities can be excited, where fluid and kinetic turbulence can arise and transfer energy between different spatial and temporal scales and where coherent long lived structures can form in physical space, such as vortices [5] and solitary waves [6], or in momentum space, such as holes [7] in the distribution function.

Relativistic particle kinematics opens a new domain in the field of plasma nonlinearities. Relativistic kinematic nonlinearities already occur at the level of single particle dynamics, as exemplified by the response of a single (test) charged particle to a large amplitude electromagnetic wave. In such a wave the charged particle motion depends nonlinearly on the electromagnetic fields because of the dependence of the Lorentz factor γ on the particle velocity v, because of the magnetic term in the Lorentz force, and because of the coordinate dependence of the wave phase. These nonlinearities are also present in the collective plasma response and lead to very important phenomena that range from the production of very high harmonics of the incident electromagnetic radiation [8], to relativistic self focusing [9] and to a local trapping [10] or enhancement of the electromagnetic energy [11]. In fact the formation of small spatial and temporal scales is a general feature of the nonlinear response of a system and provides a mechanism for increasing the electromagnetic energy density and/or the electromagnetic power locally inside the plasma without necessarily increasing the total energy of the system.

Actually, this is also the path that has been followed in order to obtain the astonishing increase in the intensities of the available laser pulses that we have witnessed in the last two decades since the advent of the technique of chirped pulse amplification [12]. Pulse compression [13] has made it possible to reach intensities as high as 10^{22} watt/cm^2 in the 1μ wavelength range and in future experiments such as ELI (Extreme Light Infrastructure) [14] intensities up to 10^{26} watt/cm^2 may be foreseen.

Plasma dynamics can be used to expand further the reach of the electromagnetic intensities that will become available. This can be achieved by exploiting the plasma nonlinear behaviour and the related process of small scale formation. Plasmas can trap and stop electromagnetic radiation, as shown for example in the case of relativistic solitons [15]. Plasmas can transfer energy coherently between different structures [16]. Indeed, a very powerful conceptual development over the last few years has been the suggestion to use relativistic plasma mirrors in order to enhance the electromagnetic energy density together with the proposal of a concrete physical scheme to realize such mirrors in the laboratory.

Again it is a sign of the outstanding development of the field of relativistic laser plasmas in the last decade that a century old idea, used by Einstein as a *gedanken experiment* in order to investigate the conceptual bases of relativity theory [17], has become an experimental tool that can be "built" in the laboratory. Relativistic mirrors can in fact be realized by controlling the nonlinear break of large amplitudes Langmuir waves in the wake of an intense laser pulse or by using the radiation pressure of an ultraintense laser pulse to accelerate thin plasma foils [18]. In these processes sheets of relativistic electrons are built that can *coherently* reflect e.g., a counter propagating laser pulse, upshift its frequency and, consequently, reduce its length and thus amplify its energy density.

The presently envisaged enhancement in field intensity could lead us to obtain in the laboratory in a not too distant future electromagnetic fields of amplitudes such that the classical relativistic particle description that we use now will not suffice [19] and, most importantly, this enhancement will allow us to obtain plasma conditions where new physics phenomena can be investigated in a *collective* multi-particle, fully relativistic system.

Already at the single particle, classical physics level it will become necessary to add to the standard Lorentz force the radiation reaction force in order to determine the charged particle trajectories [20]. At the plasma level, this is an incoherent effect related to the particle discreteness and it gives us the first indication that at high energies we will be compelled to go beyond the mean field plasma description. At even higher intensities the classical treatment will need to be abandoned and Quantum Electrodynamic effects will come into play in determining the collective plasma behaviour in the presence of a nonlinear vacuum [21]. Eventually, it will be possible to approach the critical field of Quantum Electrodynamics (the so called Schwinger field) where the generation of electron positron pairs from vacuum becomes the dominant effect in the electromagnetic field propagation [22].

Besides exceedingly high energy densities and powers, relativistic laser plasmas are also characterized by incredibly strong particle accelerations [23] as the particles oscillate at ultrarelativistic energies in the fields of the electromagnetic waves in the plasma. Through the "Equivalence principle" this opens up a new opportunity for investigating in the laboratory effects that are expected to occur under conditions dominated by gravitational effects and where General Relativity concepts must be employed. In particular effects that pertain to both Quantum Electrodynamics and Gravity can be expected to be observable in such plasma conditions, in relation e.g., to the connection between the Hawking radiation from black hole event horizons [24] and the Unruh radiation [25] that has been predicted to be perceived by an accelerating observer in vacuum because of his acceleration.

This topical issue is also dedicated to the European ELI project. This project covers the range from the design, building and operating of laser systems in the Exawatt range to the related areas of attosecond and high-field science, laser plasma acceleration and the generation and application of ultrafast X-ray beams.

What kind of new physics these developments will open up and what can be learned by having such ultrahigh electric fields available in the laboratory is the subject of the articles contained in this special issue.

The first series of articles in this topical issue identifies some new experimental possibilities offered by relativistic laser generated plasmas. A fully laser-driven γ-γ collider scheme is compared with previously proposed γ-γ collider schemes while relativistic ion colliders are shown to access, in contrast to laser plasmas, electromagnetic fields well beyond the Schwinger critical field but only for an extremely short time. The properties of ultrarelativistic electron-positron plasmas are then studied using quantum field theory at finite temperature. Several examples of photo-nuclear physics problems that may be tackled with the bright γ beams driven by intense laser pulses are discussed.

In the following series of articles some important aspects of present day laser plasma interactions are investigated analytically, such as the coherent electromagnetic structures that can trap electromagnetic energy inside a relativistic plasma, or experimentally with proton radiography e.g., in view of applications to inertial fusion diagnostics and problems related to the measurement of the pulse quality and contrast are described.

The envisaged future high-intensity laser systems will be able to probe nonlinear quantum-electrodynamic regimes. The fundamental physics problems that can be addressed in such new regimes are discussed in the third series of papers highlighting the new prospects provided by a realisation of the ELI laser facility and ranging from nonperturbative effects in quantum-electrodynamics to electron positron pair creation when approaching the Schwinger field, to the search for new particles such as axion-like particles. Special attention is given in the next series of articles to the possibility of detecting Unruh radiation as pairs of entangled photons and to the ongoing debate on the role of the Unruh and Hawking effects in the emission process of an electron in a strong oscillating electromagnetic field.

Short laser pulses at super-high intensities are then shown to be capable of opening new prospects for efficient acceleration of ions both in overdense plasmas, e.g. in an ion driven scheme of fast ignition, and in thin plasma foil configurations accelerated by the radiation pressure of the laser pulse. The importance of pulse shape control for ion acceleration is also analyzed. These acceleration processes can be affected by a range of instabilities that are characteristic of anisotropic energy flows (Weibel type instabilities) and of radiative acceleration (Rayleigh Taylor type instabilities).

New tools for generating novel and powerful sources of high frequency electromagnetic radiation are then discussed. Such tools will be provided either by harmonic generation from overdense relativistic plasmas or by coherent Thomson backscattering from ultra-thin accelerated foils or, finally, by a double “Doppler effect” where a relativistic mirror reflects a counter-propagating electromagnetic radiation. It is also shown that the coherence properties of the driving laser can be mirrored in the emitted harmonic radiation, making attosecond phase locking possible.

The predictions of the theoretical schemes for realizing in the laboratory relativistic mirrors using ultra thin foils are confirmed by the reported experimental observation of relativistic electron sheets either driven out from ultra-thin diamond-like carbon foils or formed by a breaking plasma wave in an underdense plasma.

Finally, in the last series of paper a stimulating overview is given of future developments, driven by the the results that have already being obtained in the investigation of relativistic laser plasma interactions, in different fields of physics from high energy astrophysics, to relativistic magnetic reconnection, to probing nonlinear vacuum properties to understanding the acceleration of ultra high energy cosmic rays or the origin and nature of GeV-TeV gamma-ray emissions.

Taking a sentence from one of these papers we conclude by stressing “that the development of superintense lasers with parameters in the ELI range will provide the necessary conditions for experimental physics where it will become possible to study ultrarelativistic energy of accelerated charged particles, super high intensity electromagnetic waves and the relativistic plasma dynamics”.

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