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Review

Summary of the IZEST science and aspiration

G. Mourou[1] and T. Tajima[2]

[1] Ecole Polytechnique, Palaiseau, France
[2] University of California, Irvine, CA, USA

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Abstract. Over 30 associated laboratories across 13 countries are part of the international program known as IZEST (International center for Zetta-Exawatt Science and Technology), which has been initiated and coordinated by the École Polytechique and the CEA. Together, this collaboration of laboratories are exploring new ways to push laser peak power and intensities beyond the present horizon with the aim to perform Laser-Based High Energy Physics.

Fundamental high energy physics has up to now been primarily driven by high energy charged particle colliders. The possibility to amplify laser pulses to extreme energy and peak power now offers an increasingly practical alternative which is both more compact and less expensive compared to traditional particle colliders. The principal mission of the International center for Zetta-Exawatt Science and Technology (IZEST) is to muster the scientific community behind this new concept. Here in this volume we proudly present articles from this burgeoning community on the advancement of short-pulsed lasers and their utilization for high energy and fundamental physics.

Launched in November 2012, IZEST has grown as a consortium of laboratories and institutes with a collective expertise spanning many fields of research. The common agenda is to utilize existing large scale laser infrastructure to drive and probe high energy physics and to serve as a common collaborative platform opened to the international scientific community as discussed in more details in Quinn et al. [17].

Beyond the existing petawatt scale laser infrastructure there are already a number of exawatt class facilities in the planning stages, such as the ELI-Fourth Pillar, the French PETAL and the Russian Mega Science Laser systems as well as the Japanese Exawatt Laser. With such tools offering laser intensities greater than $10^{26}\,\mathrm{W\,cm^{-2}}$ there is a resulting enthusiasm for their application to topics of high energy and fundamental physics. An example of such topics include: plasma physics, particle acceleration, astrophysics, QED and tests of dark matter and dark energy.

A key feature of IZEST is the collection of many such distinct fields within a single scientific endeavor. Such a community of scientists within the IZEST consortium can, through mutual engagement, offer considerable collective expertise crossing over multiple research disciplines. The collection of experimental facilities also crosses boundaries, where the associate laboratories can be utilized to conduct much of the preparatory work required before the moon-shot tests can be implemented at the largest scale facilities.

While such large facilities offer ultra high peak laser power, there is also a requirement to develop laser technology for higher average power which requires much higher pulse repetition rates. This is particularly important in regards the application of lasers as future particle colliders. The concept of luminosity, as used in traditional accelerators, calls for, not just high intensity, but also very high average power to deliver sufficient photon or particle numbers. When high average power is required, higher laser efficiency also becomes an important issue. This challenge is addressed in the latter part of this volume, particularly by the introduction of the CAN (Coherent Amplification network) laser concept.

With such a wide scope of science, there are formidable technological hurdles which demand surmounting in order to realize this new laser-based paradigm. The IZEST consortium have tackled this along several fronts. In the following we summarize these research directions by associating laser repetition rate with different regimes of luminosity, on which Caldwell addresses, including:

(i) exploration of the low-luminosity regime with high energy lasers;
(ii) intermediate luminosity with moderately repetitive lasers;
(iii) high luminosity regime with the CAN concept.

We also survey the primary IZEST projects including the 100 GeV Ascent, C^3 and the laser-based search for dark fields.

Low luminosity regime: Towards the Exawatt laser

A key mission of IZEST is to develop techniques that address the particle luminosities possible with laser based technology. This effort to utilize existing large scale infrastructure to demonstrate new concepts is akin to the effort made at SLAC and LHC regarding particle acceleration [1,2] and of particles such as muons as proposed by A. Caldwell [1,33]. By using existing laser-infrastructure, IZEST is suggesting a photon-analogue to the CERN or SLAC approaches where large bursts of electrons or protons are replaced by large photon pulses.

For this application a new technique called C^3 (Cascaded Compression Conversion) [3] was conceived to compress a nanosecond megajoule laser pulse to tens of femtoseconds. As described in the contributions by Frank et al. [35] as well as Malkin and Fisch [36], coupled to a plasma, the raw laser pulse can drive either an electron or an ion acoustic wave to couple its energy to a shorter seed pulse. Since the technique relies on an already ionized material, it has the inherent advantage of being essentially damageless and can withstand very large energy density, 10^4 times greater than conventional materials which means a reduction of the beam size by a similar factor, from m^2 to cm^2. The raw laser energy for such a scheme already exists in the form of the Laser Mégajoule built by the CEA in France. A common theme in IZEST is to utilize such facilities as energy reservoirs to drive pulse compression schemes to boost their laser power to exawatt and beyond.

Once created, these beams have formidable intensities and need to be manipulated and focused. The only mirror that can withstand such power is again a plasma-based mirror. A cm^2 size plasma optic would replace a m^2 mirror size optic. The technique of amplification as well as the damageless mirror concept are detailed in the contribution by Fuchs et al. [37]. The possibility to adapt femtosecond technology to megajoule infrastructure opens the door to the TeV and PeV energy. These possibilities have already found applications in the study physics beyond the standard model by T. Ebisuzaki [30] and laser-based cosmology by P. Chen [31]. Existing megajoule facilities are restricted to operating in low repetition rate $\ll$1 Hz to enable cooling of laser optics. For higher luminosities, higher repetition rates are demanded.

Intermediate luminosity paradigm: Exawatt pulses at moderate repetition rates

Applications with higher repetition in the Hz regime can be performed while producing exawatt powers using a technique described within this issue by G. Mourou et al. [39]. This technique is based on the introduction of the Thin Film Compressor utilizing the salient property that the intensity across the beam is uniform for large scale lasers, building upon the work of Mironov et al. [38]. With thin-film method, a multi petawatt pulse can be compressed into a single laser cycle, bringing the peak power of a 10 PW laser such as ELI-NP to 100 PW. Such a compressed pulse once focused to the spatial area of the laser wavelength (λ^2) is then in the ultra relativistic regime of lambda-cubed (λ^3) which has been studied particularly by N. Naumova. This possibility is a watershed enabling access to the exawatt-attosecond and even zeptosecond regime.

The compression to attosecond pulses is accompanied by a correspondingly large up-shift that transforms the initial eV radiation into keV–10 keV. This type of radiation will enable acess to the study of the quantum vacuum. It is a game-changer in laser interaction where nonlinear quantum vacuum interactions can be performed as suggested in articles by G. Dunne, N. Narozhny, L. Ji, B. King, M. Hegelich, I. Sokolov, and A. Bashinov [23–29] in this issue. Applying such X-rays mentioned above to accelerations, as shown by T. Tajima [22] in this issue, amounts to the production of particle energies in the PeV range and beyond in a compact laboratory scale.

High luminosity paradigm with the coherent amplifying network (CAN)

One of the outstanding problems affecting ultra intense lasers are their low repetition rates and correspondingly low average powers due to the poor thermal conduction of the amplifying material and unacceptable wall-plug efficiency (10^{-3}). Such issues restrict high peak power lasers from being considered suitable for important scientific and societal applications. IZEST's members have decided to take up this challenge and have led a large effort conducted by four partners (CERN, Germany, UK and France) under the aegis of the European Union to investigate the possibility to circumvent these shortcomings. The project is called ICAN for International Coherent Amplification Network. The concept is based on the massive phasing of fiber amplifiers [6,7] detailed by W. Brockelsby et al. [40] in this issue. This study demonstrates that there is no roadblock to produce peak power up to the petawatt with a MW average power implying a repetition rate of 10^4 Hz. This approach is intended to be more compact and less costly than its traditional counterparts. The large number of fibers that can be addressed independently at kHz bandwidth speed makes ICAN the first digital and heuristic laser. Such a laser would make possible the investigation of fundamental particle physics applications such as Higgs particle factory as discussed by Corner and Chou [42,46], as a dark matter research tool and in applications that need external neutron sources such as nuclear transmutation, thorium cycle, nuclear pharmacology or proton therapy.

The high luminosity produced via a CAN laser can be employed to drive X-ray sources with very high photon energy up to several 100's keV (betatron mechanism) producing collimated beams with very high compactness as compared to synchrotrons [8,9]. Several applications for such sources have been demonstrated, the most important being the phase-contrast imaging taking advantage of the micrometer source size (i.e. leading to μm resolution) [10]. The very high photon energy may find applications in material science and mechanical and nuclear engineering for radiography of bulk systems like radiator tube inspection or plane turbines and x-ray lithography.

The CAN concept has also been elegantly utilized in a new laser accelerator architecture based on phase synchronization between fibers by A. Pukhov [41] with an intention of application to the generation of TeV on a table-top in this issue.

Applications to particle accleration and fundemental physics

The lasers around the world associated with the IZEST initiative will be deployed for applications of a wide variety. In this volume the IZEST science case includes the following categories of applications: (1) laser acceleration, (2) extreme fields under which radiation effects are important, (3) nonlinear QED phenomena, (4) processes relevant to fundamental physics research and astrophysical conditions.

The laser technology aspects have been already amply mentioned in the above. Thus, in the following sections we discuss the other remaining aspects regarding application of IZEST laser technology to (1) particle acceleration to 100 GeV and (ii) the search of dark fields.

100 GeV (or Higgs energy) scale ascent

The highest intensity lasers are capable of pushing the envelope of the frontier of laser acceleration. So far, the laser wakefield acceleration [11] method has experimentally achieved up to a few GeV energy gain over a few cm [12]. It has been pointed out that in order to approach a collider relevant scheme, it is preferred to adopt a lower plasma density regime [13], as in that regime, the overall wall plug electric consumption needed to supply the lasers would go down in proportion to the square root of the electron density.

The article by K. Nakajima [19] reviews this frontier and research rationale for IZEST. Here a blueprint is presented for the laser acceleration of electrons to beyond present achievable energies. This project termed the "100 GeV Ascent" has seen much development and includes designs for implementing laser acceleration through 10–100 m plasma channels at the PETAL laser facility. Jansen [20] discusses the bubble regime scaling.

In addition to this, Zhou et al. [21] writes the consideration of the laser wakefield acceleration to injected protons (and ions) to multi-10 GeV energies with a kJ (or multi-100 J) laser. Of course, the ICAN laser mentioned above has been designed as a direct response to the challenges posed by the ICUIL-ICFA Joint Task Force Report, in which it was pointed out that the high average power and high efficiency lacking in the present laser technology needs to be remedied for high energy physics applications [14].

Dark field search by lasers

Later in this issue K. Homma [32] presents novel approaches to fundamental physics in detecting new dark particles and fields using laser photon colliders. Rationales are described by Y. Fujii [34] providing the theoretical background and motivation for such an approach. This is by searching for unknown dark fields including Dark Matter (and even Dark Energy) fields by laboratory experiments using intense and/or large energy lasers [15,16]. Such approaches may be considered as an extension of the intense laser experiments (or their Gedanken experiments) in the nonlinear QED. But they are also independently opening an entirely new way of doing fundamental physics, as has been commented, in the domain that colliders cannot explore. Such approaches exploit the two most important characteristics of lasers:

(1) a laser is consisted of massless particles of photons which low-mass dark field particles may be most sensitive to react to as long as the momentum matching is concerned;
(2) the laser beam, as opposed to typical charged particle beams which are composed of incoherent particles, are composed of Bose condensed coherent photons on the order exceeding 10^{20}.

These characteristics may give us a leaping ability to go up the sensitivity of detection, in spite of the feeble interaction between photons and dark fields.

Societal applications

In addition to these we have exciting papers of applications that have a deep impact on societal issues such as by Hajima et al., Kato, Thirolf / Habs, and Zamfir [18,43–45] in this issue. Nuclear physics and atomic energy related issues are addressed by some of the authors by employing, for example, laser-driven Compton gamma beams to explore nuclei and isotopes that will have marked resolution advantages over the conventional measurements. Its applications to nuclear medicine and nuclear pharmacology are also important. There are also broader applications to industrial frontier opening up, it has been pointed out.

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