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Review

The IZEST Framework

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Abstract. The past decade has seen a significant development of high energy laser facilities across Europe, Asia and North America. With these investments exceeding billions of euros, there is strong incentive to extend the applicability of such Big-Science infrastructure and pursue new possibilities for laser-based high energy physics. Many of these international laboratories have joined the IZEST collaboration as partners and thus will provide the facilities to carry out future pertinent experimental investigations.

1 Introduction

The International Center for Zetta-Exawatt Science and Technology (IZEST) collaboration is pursuing the concepts and applications required for the next level of fundamental physics research at novel energy and length scales. In recent years great achievements have been made at large-scale research facilities toward measurements testing our most basic understandings and models of physics–the confirmation of the Higgs particle by the researchers at CERN being the most high-profile case. New pursuits going forward–including the search for dark matter and energy – are already being considered, developed and implemented. However, despite all the recent exciting discoveries, the public has become more reluctant to fund the larger-scale facilities suggested for future research. To this end, the IZEST consortium seeks to harness and build upon the existing international infrastructure and expertise to make the leap to the next generation of projects in physics with technologies based on laser-driven plasmas. As shown in Figure 1, there are over 30 institutions and facilities associated with IZEST worldwide and there is evidently enormous potential to employ their collective resources for the future of laser-based high energy research.

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Table 1. A sample of the laser installations associated with the IZEST partnership.

Name	Country	#Beams	Power [PW]	Pulse [fs]
SCAPA	UK	3	<0.3	30
UHI 100	France	1	0.1	30
ELPHIE	France	3	<0.1	350
ALLS	Canada	1	0.2	30
PHELIX	Germany	2	0.5	500
Texas	USA	1	1	170
SIOM	China	1	>1	30
GIST	S. Korea	2	>1	30
PETAL	France	1	>1	>1
LFEX	Japan	4	1	>1
ELI-NP	Romania	2	10	15
ELI-Beams	Czech	5	10	15
XCELS	Russia	12	15	<100

Fig. 1. Current map highlighting locations of many IZEST partners across the globe.

2 IZEST's strategic structure

The framework of IZEST builds upon the existing competencies of partner research labs and institutions from around the world to further develop strategies in utilizing laser-plasma interactions. Ultimately the goal of IZEST is to implement fundamental research experiments based on the pulse compression of already-built, large-scale lasers like the Laser Mega Joule (LMJ) or the National Ignition Facility (NIF). In the preparatory phases much of the theoretical and experimental studies can be completed by scientists in collaborating countries, including France, the USA, Russia, Germany, Italy, Sweden, Japan, China, and Taiwan. In addition much of the foundational experimental experience can be gained by testing the theories developed and performing proof-of-principle studies at smaller-scale partner laser facilities, see examples in Table 1.

Since its inception in late 2012, the IZEST consortium have implemented three primary programs involving:

- laser technology and amplification such as the "C-cubed" (C3) project,
- particle acceleration which includes the 100-GeV Ascent project,
- High-Energy fundamental physics which includes the "Dark Fields" and QED group.

It is within these three divisions that the work and collaborations upon specific tasks pertaining to the overall themes of IZEST shall be envisioned and executed. Members of IZEST become associated within each area as their expertise and interests warrant. The C3 and 100-GeV projects will be quite familiar to laser and plasma scientists because, in many ways, they pertain to the expansion and improvement of laser and particle acceleration technologies. However, the Dark Fields project recognizes that laser intensities are reaching a point that allows for applications to high-energy physics, a realm typically employing traditional accelerators. As laser technology becomes complementary to this energy regime it becomes a new playground for theorists to explore and propose new tests for our understanding of fundamental physics.

The following sections are brief summaries of each division within the IZEST consortium.

2.1 Laser technology

The IZEST strategy will explore a number of new methods for laser amplification using conventional and novel technology. As discussed by Tajima & Mourou in [1] there are a number of distinct regimes of repetition rate, peak power, average power and luminosity of laser drivers for fundamental and applied research. A significant infrastructure already exists in the form of short puled TW-PW lasers complemented by large energy facilities such as the NIF and the LMJ. Coming on-line within the decade are large user facilities including the ELI pillars, PETAL, APOLLON and EXCELS which will approach the exawatt regime. Critically, IZEST is committed to developing strategies for implementing novel compression technology within this infrastructure in order to supersede their inherent laser power to potentially zettawatt levels.

As an example, a principle project in IZEST involves the unification of three laser compression techniques: Chirped Pulse Amplification (CPA), Optical Parametric Chirped Pulse Amplification (OPCPA) and Plasma Compression (PC) using Raman and/or Brillouin Amplification. This amplification chain is dubbed Cascaded Conversion Compression (C^3 or C3) and has the capability to compress nanosecond laser pulses in the kilojoule to megajoule range down to femtosecond pulses with an excellent efficiency so that pulses with exawatt-and-beyond peak power are predicted. The very small beam size (≈cm) together with the low repetition rate laser system will allow for the use of inexpensive, disposable, plasma-based optics that offer the promise of focusing with f-numbers not achievable with conventional optics to a spot size on the order of the laser wavelength, as described in [11]. As the intensities approach the Schwinger value, it opens up new possibilities in fundamental physics. This C^3 approach could be implemented at current large-scale facilities and open the way to zettawatt level pulses. Research on the physics of plasma-based amplification has been ongoing and recent results regarding stimulated Brillouin back-scattering and resonant backward Raman amplification can be found in [9, 10].

Another new compression technique termed “Thin-Film Compression” is presented for the first time in [12] by Mourou et al. Complementing these approaches is the development of a high-repetition and high efficiency rate laser system under the ICAN project. Here, diode pumping of >10 k optic-fibers together with novel phase recombination and CPA technology is heralding an exciting future for practical laser-based applications as discussed in [13] by Brocklesby et al..

2.2 Particle acceleration

Laser driven plasma accelerators have evolved to producing ultra-short pulses of multi-GeV electrons and ≈0.1 GeV protons. By virtue of the >100 GV/m electric fields attainable in plasma media, GeV energies are reached after only centimeters of acceleration.

A key long-term objective of the IZEST framework is the pursuit of accelerators capable of TeV energies to enable investigations of fundamental physics in succession of traditional RF accelerator technology. The first phase of this ascent is the goal of 100 GeV for laser plasma acceleration of electrons.

The "100 GeV Ascent" project within the IZEST framework has been in development since 2012 and is led by K. Nakajima. Here, the challenges include scaling the plasma length from $10^{-2} \rightarrow 10$ m and the density from $10^{18} \rightarrow 10^{16}\,\mathrm{cm}^{-3}$ together with the laser energy from $10 \rightarrow 10^{3}$J to achieve a similar magnitude increase in electron energy. These challenges are to be met by employing a strategy of scaling the technology and science in increasing steps at existing laboratories within the IZEST global network. The current strategy of this ascent includes:

- CEA France: Injector R&D
- KEK Japan: Plasma Waveguide R&D
- Univesity of Strathclyde UK – SCAPA: Diagnostics, 10 GeV
- GIST-CORELS S. Korea: Multi-stage 20 GeV
- SIOM China: Multi-stage 30 GeV
- GSI Germany- PHELIX laser: final testing → 50 GeV
- PETAL France: full demonstration → 100 GeV.

Through such a staged process of R&D and a succession of experiments at intermediate scale facilities, the science and technology can be established and tested before full demonstration at the largest existing facilites such as PETAL at the Laser MegaJoule.

2.3 Fundamental physics

With increasing laser intensity towards $10^{26}\,\mathrm{W/cm}^2$ and beyond, there are opportunities to investigate new areas of fundamental physics. These areas represent the exciting convergence of high-intensity lasers with high-energy physics. Here fundamental physics includes weakly interacting phenomena such as Dark Matter, Dark Energy, nonlinear QED effects, Higgs production and quantum vacuum studies.

The Dark-Fields project group within IZEST was launched with the title "Dark" to include the broad sense of something undetected by conventional experimental approaches. The methods that become available when utilizing high-intensity as well as high-energy laser fields open the possibility for the study of many new subjects.

A current search regards weakly interacting low-mass bosons as a candidate of dark fields via quantum optical observables such as four-wave mixing where the nonlinear atomic process in matter is replaced by a nonlinearity caused by a resonantly exchanged light boson in the vacuum. Preliminary experimental trials to search for the four-wave mixing process are on going at Kyoto (Advanced Research Center for Beam Science, Institute of Chemical Research, Kyoto University in Japan) and further tests are planned at INRS under the association of IZEST.

In addition to the Dark-Fields program, there are many other fundamental projects being developed within the IZEST framework and are detailed in this volume. A number of articles investigating laser particle pair production by QED effects are contained in [2–8] and the production of Higgs bosons through gamma-gamma collisions driven by laser-electron scattering is described in articles by L. Corner and W. Chou in [14,16].

3 Laser facilities within the IZEST framework

The model of coordinating efforts across a wide range of facilities has already been mentioned and comprises a complementary range of scales for carrying out IZEST investigations with a strategy of staging the development from smaller-scale laboratories in preparation for implementation at increasing levels. The scale here typically corresponds to the available laser power, number of laser beams and the physical size of the interaction chamber(s). An overview of many of the laser installations associated with IZEST is shown in Table 1. In addition to this list, the following section focuses on four facilities coming online. The goal here is to provide a brief summary of the novel high-energy laser and beamline tools becoming available to physicists in the near future and, especially, to highlight their relevance within the IZEST framework for pursuing fundamental physics.

3.1 The Laser Mega Joule and PETAL laser facilities

The laser Megajoule (LMJ) system, developed by the French Commissariat l'Energie Atomique et aux Energies Alternatives (CEA), is under construction at CEA/CESTA near Bordeaux. At a primary stage, the system will deliver 1.3 MJ comprised of 176 beams of 0.35 μm light onto target. LMJ is designed to provide the experimental capabilities to study High Energy Density Physics (HEDP), and will be a keystone of the French Simulation Program, which combines improvement of physics models, high performance numerical simulation and experimental validation.

The PETAL project is the addition of a short-pulse high-energy beam to the LMJ multi-beam facility. PETAL will deliver kJ of laser energy within 0.5–10 ps pulses which can be synchronized with the nanosecond beams of the LMJ.

The PETAL/LMJ facility will be an exceptional tool for the IZEST community with planning already begun for particle acceleration and laser-plasma amplification experiments. In terms of the 100 GeV project much work has been carried out in designing plasma wave-guides for acceleration by laser wakefields in large-scale (10's of meter) and low density plasma. These are unprecedented conditions in a laboratory. Using the Cascaded Compression Conversion (C3) scheme, which couples CPA, OPCPA & Backward Raman (or Brillouin) Amplification, extreme laser power and electron energy could be obtained. On the other hand, accelerated ion beams offer new opportunities for development of compact ion accelerators. Control of the ion beam (*i.e.* energy selection, divergence control) could lead to medical applications such as hadron therapy. Since the building has been commissioned in December 2008, the LMJ is on schedule for the first commissioning experiments to begin by the end of 2014. Experiments with PETAL will begin in 2016 giving us the possibility to address new frontiers in high energy physics open to the scientific community.

3.2 ELI

The Extreme Light Infrastructure consists of a number of large user facilities being constructed in Europe to pursue laser-based high energy physics. Here we will summarize 2 pillars of this infrastructure termed ELI-beamlines and ELI-NP associated with IZEST.

ELI-Beamlines has been designed for the generation of ultra-short energetic particles (>10 GeV) and radiation (up to a few MeV) beams produced from compact laser plasma accelerators. It is expected to support ultra-high field science, *i.e.* access of the ultra-relativistic regime encompassed within the IZEST framework. The laser resources at the ELI-Beamlines facility are designed to address the areas of laser acceleration, generation of high-brightness X-ray pulses, and high-field physics. The generated ultra-short pulsed sources of energetic particles and radiation will serve for fundamental research and multidisciplinary applications.

The development, research and engineering activities within the ELI-Beamlines project are structured into six Research Programs:

1. Lasers generating separate ultrashort pulses and multi-petawatt peak power: a) High-repetition rate and high average power laser pulses delivering multi-10-TW to PW peak power, using laser-diode-pumping technology, b) Ultra-high peak power of 10 PW, providing focused intensities up to 10^{23} W/cm^2, using innovative technology capable of operation at increased shot rates.
2. X-ray sources driven by ultrashort laser pulses: plasma-based X-ray lasers, plasma betatron, advanced K-alpha sources, high-order harmonic generation in the keV region, and compact X-ray free electron laser. Applications of the femtosecond X-ray flashes for phase-contrast imaging, XUV and X-ray holography of complex cells and proteins, study of the very first steps of biochemical reactions.
3. Particle acceleration by lasers with energies achieving several tens of GeV and of protons/ions with energies achieving several GeV and development of repetition rate proton/ion monochromatic sources with energy between typically 200 and 250 MeV.
4. Applications in molecular, biomedical, and material sciences to enable research in molecular, biomedical, and material (MBM) sciences, using ultrashort XUV/X-ray and particle secondary sources, as well as the primary IR laser pulses.
5. Laser plasma and high-energy-density physics: nonlinear optics of plasmas and laser interactions with underdense plasmas, relativistic plasmas, laser interaction with solids/clusters/mass-limited targets, generation of warm dense matter and physics of advanced fusion schemes, especially of fast ignition. With jitter-free synchronization of pulses delivered by different beamlines, it will be possible to perform various interaction experiments with preformed plasmas and sophisticated pump-probe experiments.
6. High-field physics to explore specific themes of the ultra-relativistic regime of laser-matter interaction, with focused intensities exceeding 10^{23} W/cm^2. Exotic experiments will include electron-positron plasmas, vacuum four-wave mixing, vacuum polarization and vacuum birefringence, Unruh radiation, QED cascades, and quark-gluon plasmas.

Since the ELI-Beamlines project was signed on August 2011 systems engineering has been included and a significant amount of work has been made. Nevertheless the delivery date of the project as a user's facility will not be before 2018 although planning can indeed commence for IZEST related endeavors.

The Nuclear Physics facility of ELI (ELI-NP) will consist of two components:

1. A very high intensity laser, where the beams from two 10 PW lasers are coherently added for a high intensity of $10^{23} - 10^{24}$ W/cm^2 or electrical fields of 10^{15} V/m.
2. A very intense ($10^{13}\,\gamma$/s), brilliant γ beam, 0.1% bandwidth, with $E_\gamma >$ 19 MeV, which is obtained by incoherent Compton back scattering of laser light from a very intense electron beam ($E_e > 700$ MeV) produced by a warm linac.

This infrastructure will create a new European laboratory with a broad range of science covering frontier fundamental physics, new nuclear physics and astrophysics as well as applications in nuclear materials, radioactive waste management, material science and life sciences. ELI-NP will allow either combined experiments between the high-power laser and the γ beam or stand-alone experiments. The γ beam will have properties unique in the world and opens new possibilities for high resolution spectroscopy at increased nuclear excitation energies. This promises to lead to a

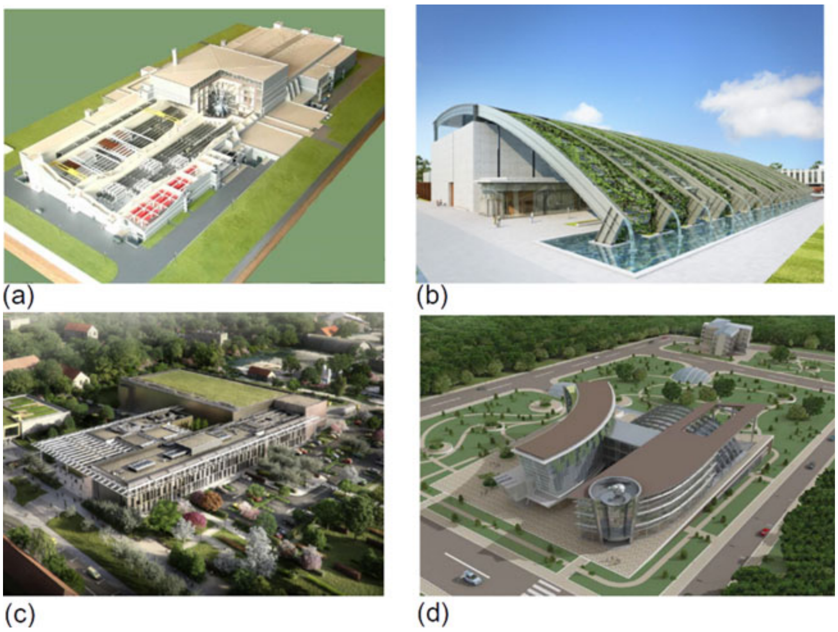

Fig. 2. (a) Laser MegaJoule, (b) ELI-NP, (c) ELI-Beams and (d) XCELS.

better understanding of nuclear structure at higher excitation energies with many doorway states, their damping widths, and chaotic behavior, but also new fluctuating properties in the time and energy domain.

The new types of neutron sources and positron sources may become of great importance in material and life sciences. The high power laser allows for intensities of up to 10^{24} W/cm^2. Here very interesting synergies are achievable with the γ beam and the brilliant high energy electron beam to study new fundamental processes in high field QED. The use of the very high intensity laser and the very brilliant, intense γ beam will achieve major progress in nuclear physics and its associated fields like the observation of the first catalyzed pair creation from the quantum vacuum. In ion acceleration the high power laser allows for the production of 10^{15} times more dense ion beams than achievable with classical acceleration. With this type of new laser acceleration mechanism very significant contributions to one of the fundamental problems of astrophysics can be addressed – the production of the heavy elements beyond iron in the universe. The cascaded fission-fusion reaction mechanism can then be used to produce very neutron-rich heavy nuclei for the first time. These nuclei allow for the investigation of the $N = 126$ waiting point of the r-process in nucleosynthesis. Further details regarding ELI-NP can be found in the article by N.V. Zamfir in [15] of this volume.

3.3 XCELS

The Exawatt Center for Extreme Light Studies (XCELS) is designed to establish a large laser research infrastructure in Russia. The core of the planned infrastructure will be a unique source of light having the power of about 0.2 Exawatt. This source constitutes a 12 channel × 15 PW laser system based on optical parametric chirped pulse amplification (OPCPA) techniques. The corresponding laser architecture was developed at the Institute of Applied Physics in Nizhny Novgorod (IAP) where the first Petawatt-class OPCPA laser in the world, called PEARL, launched in 2007 and a multi-Petawatt system is currently under construction.

The fundamental processes of laser-matter interaction at exawatt powers pertain to an absolutely new branch of science that will be the principal research task of this infrastructure. For IZEST, the EXCELS system will enable opportunities for studying the space-time structure of vacuum, nonlinear QED phenomena and unknown processes at the interface of the high-energy physics and the high-field physics.

The first phase of the XCELS Project is the prototyping phase. It includes creation of two modules with the power of 10 PW at the premises of IAP by the end of 2016 and will be a natural continuation of the PEARL project. Creation of the sub-exawatt laser will be performed at the implementation phase starting from 2016 that is supposed according to the prospective federal budget of Russia. To accommodate XCELS, a ground area of about 5 hectares in the vicinity of the city of Nizhny Novgorod will be engaged and a new research building will be constructed by the year 2019 for hosting of about 300 researchers and technicians. A detailed overview of EXCELs is given by Bashinov et al. in [8] of this volume.

Conclusion

There is a wide spectrum of topics that are relevant to the IZEST collaboration – ranging from the engineering of laser systems to the theoretical and experimental models of pure vacuum– and it becomes difficult to highlight all of these aspects in one document. One point that is important to note is the wide range of backgrounds and nations involved in developing this next level of physics. Science advances through technological progress that leads to new observations and models. Often theory informs our discussions and planning but ultimately it must be compared with experimental observations. Moving forward one sees the requirements for scientific advancements in high-energy physics requiring large collaborations that span the globe and draw upon the resources of a network of laboratories to proceed. The International center for Zetta-Exawatt Science and Technology is organizing a laser-based community in preparation for the near-term applications that new high-intensity facilities present to the broader physics, medical, and general populations.

The PETAL project is being performed under the auspices of the Conseil Régional d'Aquitaine, of the French Ministry of Research and of the European Union and with the scientific supports of the Institut Lasers et Plasmas.

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