Science of Extreme Light Infrastructure

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Abstract. The infrastructure of Extreme Light Infrastructure (ELI) provides an unprecedented opportunity for a broad range of frontier science. Its highest ever intensity of lasers, as well as high fluence, high power, and/or ultrafast optical characteristics carve out new territories of discovery, ranging from attosecond science to photonuclear science, laser acceleration and associated beams, and high field science (Four Pillars of ELI). Its applications span from medicine, biology, engineering, energy, chemistry, physics, and fundamental understanding of the Universe. The relativistic optics that intense lasers have begun exploring may be extended into a new regime of ultra-relativistic regime, where even protons fly relativistically in the optical fields. ELI provides the highest intensity to date such that photon fields begin to feel even the texture of vacuum. This is a singular appeal of ELI with its relatively modest infrastructure (compared to the contemporary largest scientific infrastructures), yet provides an exceptional avenue along which the 21st Century science and society need to answer the toughest questions. The intensity frontier simultaneously brings in the energy horizon (TeV and PeV) as well as temporal frontier (attoseconds and zeptoseconds). It also turns over optics of atoms and molecules into that of nuclei with the ability to produce monoenergetic collimated γ-ray photons. As such, the ELI concept acutely demands an effort to encompass and integrate its Four Pillars.

Keywords: extreme fields, high field science, attosecond science, laser acceleration, photonuclear physics, vacuum physics.
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I. THE OVERALL ELI SCIENCE CASE AND THE FOUR PILLARS

The project of ELI and its promise of science are extraordinary. It is timely and can be done, and at the same time it is not at all an extension of what we have now, but rather to push the envelope as far as we can possibly imagine. Thus this constitutes a bold and unprecedented proposal that leaps the intensity of laser by some three orders of magnitude. Now there are large clusters of research centers that will harbor PW lasers, but none will approach remotely close to what ELI promises. It will pass by the current regime of relativistic optics and catapult itself into an ultrarelativistic intensity regime in which even protons begin to fly relativistically. This is a singular appeal. Harnessing this is a major opportunity for 21st Century scientists.

The philosophy of providing ELI as a user facility (or a cluster of user facilities) for a broad community is an admirable one, though it certainly points to thrusting breakthroughs in an unimaginable category as well. The Grand Challenge Conference has suggested four Grand Challenges: laser acceleration, vacuum physics, attosecond science, and photonuclear science (or sometimes three pillars in the ELI Science Case document. These three pillars are: attosecond science, high field science, and high energy beam facility. The third closely corresponds to the Grand Challenges of laser acceleration and photonuclear physics. Now on GCs and pillars will be interchangeably used). We regard that this philosophy is a noble and yet quite wise one, though some may say that we should carve out the most unique and sharp goals only. Though the latter has some point, we believe that this broad and yet deep and layered science goals with multiple pillars are what ELI is really unique about among the contemporary large and acute science projects, where too often the projects are nearly single-purposed and too narrowly (or too 'precisely') defined, not allowing 'the nature to talk to you, rather than we squeeze the nature to let say something'. We recognize that ELI is not a single purpose facility, but rather a discovery machine that may happen to open up the hidden doors of nature to us with the unprecedented parameters of laser such as intensity and pulse length. Some may say that this is a bit of a break from the latest large scientific instruments that have fairly narrowly defined missions; it may resemble more with telescopes, with which we improve its acuity in an unprecedented level to wait to see whatever it affords to show us. We should not forget that the strength and uniqueness of ELI are derived from this unified whole, not from each of four pillars. We thus emphasize the importance of the overall integrity of ELI.

With this philosophy of ELI understood, we praise the choice of four pillars. On the surface, for example, one may say that the attoscience is not as protuberantly salient and unique to ELI as other pillars, or one may say that laser acceleration may be either too low-energied and or not exceeding what the conventional technology offers, etc. All these are true. Yet, with deeper consideration, we recognize that there are, as we suggested above, structured depth to the kind of science ELI tries to unravel. The unprecedented intensity ELI tries to bring in entices us to imagine for the first time to ‘break vacuum’, which is certainly a fascinating, albeit far-fetched and faraway, goal. Even contemplation of such may lead to an entirely new discipline of physics that only several years ago virtually unimaginable and nonexistent. Yet, ELI promises exploring not just this single goal, but rather varieties of characters of science it can pioneer. Attosecond science may lie at our forefront of achievements. We note here that Professor Mourou's contention [1] that the higher the intensity the light source is, the shorter the pulse length and the higher its frequency are as part of his dictum. Based on this philosophy and observation, it is recognized that the ELI intensity would bring out far shorter pulse and far higher frequency light (or coherent X-rays) as ever before and thus the attosecond science [2,3] will be certainly boosted further beyond the atomic principle of today. Furthermore, as we later detail the ELI capability to deliver both (coherent) intense high-frequency photons synchronously with the laser itself, one can conduct unique pump-and-probe measurements in attoseconds with unprecedented flexible settings that are suitable for dynamical studies. In this sense the attosecond science sits in front of us for our exploration, providing us a broad piedmont of a huge mountain. On the other hand, the vacuum physics may constitute the sharp and lofty apex of the mountain of science. In the same token, perhaps the laser acceleration portends to be the high plateau above the piedmont, while the photonuclear science presents itself as the high blue mountains surrounding the apex.

We surmise that the ELI science structure is well-defined as a heaving large mountain of science, rather than a strutted spear without skirts. This structure of science, we also recognize, supports broad societal applications. The ELI science of attoseconds, for example, will usher in dynamical structural studies on small objects with unprecedented time resolution [4]. Laser acceleration [5] not only explores the laser electron collider technology, but also offers the unique combination of such high energy particles precisely synchronized with photon beams, rendering a natural marriage of photon and charged particles. With its ultrarelativistic dynamics of the ELI intensity, we also anticipate compact and brilliant ultrarelativistic ion beams driven by laser for the first time [6]. This itself and laser Compton scattered gamma-rays [7] open a door to the birth of what may be termed as photonuclear physics. Directed monoenergetic high-energy pulsed brilliant gamma-rays now should serve as the bedrock for exploring nuclei [8], just like the laser has done so for atomic structure since 1960. With the ever-shortened time-scale of even zeptoseconds that may match the timescales of nuclei, we can see nuclei that may not be reachable by charged particle collisions. As to the 'feel the texture of vacuum', the unprecedented strong fields themselves as well as the combination of the intense laser and counteracting high energy laser-driven electron beams, for example, can enter extreme field physics that have never explored to date [9]. Rather than the more traditional particle physics method of high momenta, ELI will usher in an instrument with high amplitude (at near zero momenta). Such an instrument, we believe, is in fact very exciting and at a cutting edge of science. The pillar of laser acceleration, on the other hand, may provide knowledge toward a path to scale up energies of particle much beyond the conventional accelerators can attain, such as 10–100 TeV and PeV [10,11], albeit with small number of particles, where a non-luminosity paradigm of physics such as the vacuum texture detection due to quantum gravity [12,13] may be explored [11].

The ELI Grand Challenge meeting [14] by the scientific community and the ongoing CDR (conceptual design study) and TDR (technical design study) activities inside of ELI have reflected very nicely the above science scope. Either through the three pillars in the Science Case document ((i) high field science; (ii) attosecond science; (iii) high energy beam facility) or these four Grand Challenges, we recommend to forge strong research proposals in a concrete fashion with the involvement of the respective world's scientific community to spearhead the further development of these research lines. ELI should run ahead with this enthusiastic research program and make presentation to the community calling for participation. Such may be based on the already emerging leadership of GC teams or Scientific Working Groups, Virtual Institute, or newly added blood of scientists and/or countries. Also noticed is the strong interrelationship of these four areas so that cross-fertilization should be encouraged among the fours areas. Perhaps, to further concretize this activity will culminate in emerging research teams with well-defined PI to promote specific research proposals further downstream. Such research proposals may be coordinated with ELI Management as well as to pursue some necessary external funding for such items as detectors and other scientific instruments that are not necessarily inherently part of ELI.

II. SITE-RELATED ISSUES

ELI is a facility of revolutionary capability, which will create new science, new scientific constellations, and a new scientific community. The Steering Committee on Oct. 8, 2009 has decided [15] to award three countries (Hungary, Romania, and Czech Republic) the sites of ELI centers for attosecond science, photonuclear science, and laser driven beam facility, respectively. This is great news. First, the ELI is decided to go ahead with a real budget. In fact, it is the first of the EU's project 'European Strategic Forum for Research Infrastructure' (ESFRI) to proceed. Second, these centers are to be located in emerging countries. In fact it is the first major scientific infrastructure to be located in such countries. This is very encouraging, as the science of extreme light will have a much broadened base and science will benefit for that and the scientific community will be that much richer for that.

Third, instead of one overall center, there will be three centers, respectively, and the fourth may be at another site. On one hand, these distributed centers may help stimulate the layered and broad development of ELI science. On the other hand, as we emphasized in Sec. I, the integrity of ELI science may be at risk, if there is a proper safeguarding against a possible lack of coordination and integration of the ELI science is not installed. We regard that this is a principal challenge of the current site choice for three sites. We strongly urge that (i) there be a strong governance mechanism that reinforces the integrity of the overall ELI science and, (ii) there be a strong cross-fertilization and joint projects among the three centers to stimulate mutual cooperation and complementary collaboration, and (iii) we should not forget about the fourth pillar of high field science. These should ensure the science of ELI to gain the breadth and depth simultaneously and break the ground for truly unique and novel scientific endeavor that the world needs, envies and wants to participate in.

On the other hand, each center should be allowed not to stop or slow down, because the other center is slow or delayed. Time is money.

III. FACILITY AND ITS CHARACTERISTICS

ELI is a facility of highest laser intensity ever. It is also a community facility that serves a wide spectrum of science in Europe and beyond. The scope of science, as we described already above, is composed of multiple pillars with breadth and depth of science. It is also, we regard, a discovery machine of physical (and other) regimes mankind never treaded before. In order to meet these scopes, the facility is composed of a front end (up to 100 Hz) [16], booster beamlines with 1–5 PW (2 of them DPSSL (diode pumped solid-state lasers) [17], pumped at 10 Hz), to a shot per minute highest powered 100 PW. Also it leaves a room to grow toward 200 PW. The final duty amplifiers come in 10 lines. Separate from this staged high field main-line facility, a DSPPL-driven high repetition 0.1 PW attosecond science applications laser with 1 kHz repetition rate is also planned. The staged design is not only natural, but also wise in two senses. First, it allows to incrementally develop and thus one can test lower powered stages first and even begin using them before higher powered stages come on line. This way one can drive the science program in certain pillars to start earlier and the community surrounding the facility to emerge at early times. Second, this will reduce the technical and financial risks.

Even though it is not our primary task to evaluate the laser facility itself, it is worth mentioning some of the impressions we got here.

(i) The employment of the technology of DPSSL for beam-lines that use higher repetition rate is a wise design, for which beam brightness and particle fluence etc. count for these classes of experiments. Meanwhile this technology remains quite expensive, one may not be able to afford to sweep with this completely. It is understandable that the high repetition demanding attosecond science applications laser is pumped entirely by DPSSL. By keeping 2 lines with DPSSL for the beamlines (few PW level), it allows crossover utilization between the mainline laser and the attosecond science applications laser.

(ii) The preparation and maintenance of highest powered laser optics (including the lasing crystals) are a feat of technical challenge. The average power throughput on gratings, for example, is quite high. The optics with this tremendous power may suffer, for example, heating and small-scale self-focusing etc., which could distort the phase and amplitude of the amplified laser. Even a relatively minute distortion can accumulate a fatigue and defects in the optics, which in turn could lead to damage. This can be dangerous and expensive. In order to avoid this problem, one needs a sophisticated monitoring system as well as accurate remote control of all systems in real-time. High finesse to control all these laser phases within a fraction of phase angle is required. Sophisticated beam cleansing etc. are required. Even with these, it is still not quire sure if we can all control possible distortion of phase front distortion of laser, say by a defect in crystal or some other impurities and fluctuations. This may pose a considerable risk. Many of these issues are common in other projects with high power lasers such as in fusion. Thus some of the solutions may be borrowed from these and / or collaboratively addressed. We hope that the highest caliber of the technical expertise of the ELI team will be able to handle this challenge successfully.

(iii) Similarly, the final amplification stage takes multiple lines and one needs to coherently superpose them, as many as 10 or so at the highest power. This is a challenge that the world has never encountered nor has been carried out at this level. We understand that at Rutherford Lab and at APRI in Korea they are testing the merger of two large energy short pulse lines. With this kind of experience sharing, a risk may be reduced for this difficult task.

(iv) We commented that they felt that an advisory committee to assist the technical development may be needed here. This is because of such high challenge. Exactly what type of technical assistance and / or review is most appropriate is not a trivial question. Different from this SAC committee, which focuses on science and detached from the minute developmental and technical operational issues of lasers, this technical advisory function may be done either by a machine technical committee with productively directed advice or a team of some organized consultants or in-between. The ELI Management should find an optimal function of such technical advisory function that helps most toward this goal. Some of the enhancer technologies and some aspects of issues that may have slipped the ELI team's attention may be best addressed, absorbed or transferred by some advisory mechanism.

(v) We felt that some of the targeted specifications of the laser are not sufficiently clear. Some felt that what constitutes 'success' is not sufficiently clearly stated. These questions are of both technical nature and managerial one. Considering the philosophy of the ELI being a broad facility for a mountain of Grand Challenges (as discussed in Sec. I), a breadth and flexibility may be allowed for room to maneuver and grow out of a challenge. Nonetheless, a clearer table of parameters is helpful.

(vi) The facility will produce unprecedented high energy photons and other particles of unique nature. This quickly brings in a severe problem of the issue of heavy radiation shielding [18]. It may cause a serious restriction of usage of solid targets. New thinking on how to reduce radiation and dosage may be needed. Here an idea such as that since many particle bunches are of ultrashort ones, an efficient collective deceleration method (wakefield deceleration was mentioned in the GC Workshop) may be employed to considerably reduce a large portion of energies of high energy particles without causing radiation [19]. A flexible design to cope with future developments may be necessary.

(vii) Many of us felt that experimental areas and detector areas are very important. To allow sufficient room and growth needs a wise design and flexibility. It also calls for early proposals by the scientific community to suggest the major projects and associated experimental plans. These have to be meshed with the ELI Management as early as realistically possible. In particular if and when a big idea is suggested, the experimental area needs to be able to accommodate such.

(viii) The spherical focusing onto nm scale interference patterns is casually described. Since it is intriguing but not well tested, we recommend such a method to be tested on a more conventional laser facility for a proof-of-principle, before it is introduced to ELI.

IV. MANAGEMENT

The overall management philosophy and structure seems robust and reasonable. The leadership is clearly seen, as well as the vision of the program is nicely projected out, attracting a large and strong following of enthusiasm across many countries and scientists of various disciplines. The management is conscious of the need to embrace the broad scientific, administrative, societal, and political spectrum, while the project needs to be hailed as a cutting edge of the 21st Century science. It has admirably balanced this delicate matter.

It is evident that the issue of the site selection is important, where even more sensitive balancing of the breadth of the community and the towering peak of the expertise needs to be carefully weighed. This is also culturally very sensitive and we need to be so, as mentioned in Sec. II. The management needs to be flexible to adjust to various possible scenarios that may arise.

One of the repeated comments has been to the recommendation to ensure sufficient and yet not overly constrained infrastructure for scientific applications and detectors. We recommend that the Management and scientific community such as the stakeholders in GC Leaders and other forms need to talk and draw plans so that some concrete infrastructure may be planned. Included or at least considered among these is such infrastructure as theoretical and computational divisions. Even more important is the broad applications divisions that match well with the science programs. Fortunately, the ELI structure with broad pillars allows a natural way to take this large latitude of applications program.

Some recurrent comments were to define the machine parameters more clearly as well as definition for success more clearly to help the management and funding agencies to handle the progress of matrix more transparently. This is a delicate matter, we realize. While the management needs to understand and manage the resource and manpower distribution etc. so that the goals can be adequately reached, the staged structure of ELI may allow robust and flexible management possible. We leave the ultimate management style to the Management to decide what to take.

The technical advisory function was discussed already in Sec. III.

As discussed in several different places, the management needs to bridge to, stimulate collaborative and complimentary relationship with neighboring disciplines, such as the accelerator physics community, X-ray free electron laser [20] (Xfel, while the European X-ray Free-Electron Laser is called XFEL) community, etc. In order to enhance broad community's involvement, such an idea of a Virtual Institute may be useful. Also, it may be highly desirable to develop a nice networking relationship with the existing PW class labs and emerging labs so that the overall scientific program in the world can be efficiently organized and communicated for mutual scientific camaraderie and without unhealthy excessive overlaps and overcompetition. These nice complimentary relationships may allow for a healthy scientific decision making body (or bodies) to emerge.

To bootstrap the resolution of issues and progress that have been raised at this GC meeting, it is recommended to have a meeting at which these can be reviewed and further ascertained and spurred.

V. FOUR PILLARS OF SCIENCE ISSUES

1. Attosecond Science

It is probably fair to say that attosecond science has begun only relatively recently, but has exploded quite rapidly during the last decade. It has captured electrons and atoms in stroboscopic fashion for the first time. We should capture the structure of matter very precisely in years to come with the technique of attosecond science, because attoseconds are the characteristic time of (atomic) electrons. Since attoseconds are shorter than the optical period, it is natural to pursue ever higher frequency photons to reach this ultrafast timescale, such as HHG (higher harmonic generation) [21]. In order to resolve atomic time scales, it may be deemed natural to employ atoms to generate HHG photons and their associated timescales at attoseconds. The attosecond science now envisages to leap from the current status based on this paradigm typically with nJ pulse energy and 100 eV (< keV) photons and 10s of as, to mJ pulse energies and 1–10 keV photons and less than as time scale. This would enable attosecond X-ray pump and attosecond X-ray probe, for example and also nonlinear X-ray science. With the synchronization of the all optically generated pump and probe, we now anticipate the *dynamics*, rather than or beyond the *structure*, of matter, e.g. in strongly coupled solid state quantum states. Such may not be realized with the current standard-bearer of laser irradiation of gaseous atoms via HHG because of the medium depletion via ionization.

We need a more intense laser to harness attosecond light sources with more brilliance, higher frequency and shorter pulse length, introducing mechanisms such as relativistic dynamics of electrons organized in (or around) solid (or other) matter by its strong and robust fields (such as Volkov fields) (instead of relying on the quantum mechanical self-organized structure of atoms) [22]. At ELI the AttoSecond Light Source (ASLS) is planned. This plan is fitting to satisfy this need, based on the envisaged capability unique to ELI. The current attosecond technology demonstrated so far by the community relies on the use of a strong, waveform-controlled, few-cycle laser pulse either as a pump or as a probe in addition to the rather weak attosecond XUV/SXR pulse. This is because the attosecond pulses are too weak to be used both as a pump and as a probe simultaneously. It may be that the hope to change this unsatisfactory state of matters by the simple improvement of a laboratory-scale attosecond source is rather bleak. Intense attosecond pulses from ASLS hold promise for opening the door for the first time to attosecond nonlinear XUV and X-ray science and hence attosecond XUV/X-ray-pump/XUV/X-ray-probe spectroscopy. With its brilliance and short-pulse natures ELI promises to go much further via the relativistic dynamics of the interacting matter such as a thin solid target under the relativistically intense laser fields. For the relativistic optics of intense lasers with $a_0 \gg 1$, the electron dynamics is strongly nonlinear, which contributes to the large frequency multiplication and pulse compression much beyond the atomic dynamism does. This includes the relativistic oscillating mirrors [23], relativistic sliding mirrors [24], relativistic flying mirrors [25], and relativistically driven transmitted photons through ultrathin layers [26]. In these cases with proper control it should be possible to shape the attosecond pulses, not just to compress these. It is foreseen that with this enabling development of techniques, for example, structural biology [27] at its current forefront of science may be surpassed and transformed into dynamical biology, where we would observe not a static frozen structure of a molecule, but rather witness vivid living life to exhibit dynamical behaviors. Finally, another ELI characteristic is high average power and thus very high (kHz) repetition rate of VUV radiation. The employment of the DPPSL technology for the sake of the higher repetition rate and higher efficiency capability to the ASLS makes sense.

Having written like this, it occurs to us that some of these capabilities come across those with Xfel. We wish to make some comparison with Xfel promises below. The lower line shows expected HH parameters using ELI´s high power capabilities with intensities of 10^{20} W/cm^2 at the fundamental wavelength of the laser.

TABLE 1: Specifications of current and future laser-based attosecond radiation sources, taken from the Charambilidis TDR document) [28]. (Recently in Nature Physics [29] the phase coherent generation of relativistically driven harmonics from solids has been shown, allowing for attosecond pulse bunching.) In this table, for example, the surface HOHG [30] from ELI might extrapolate its frequency at an even higher value of $a_0 = 10^3$ to yield even MeV from the γ^3 scaling, even though it is hard to imagine how the solid surface reacts to such intense fields. It is needed to investigate how these extrapolate or saturate.

Source	$\hbar\omega$	τ	E *(@ the source)*	I_{max} *(@ the target)*
Gas HOHG single pulse	20 -100 eV	~ 100 asec	≤1 nJ	$<10^{11}$ W/cm^2
Gas HOHG pulse trains	10 -100 eV	≥ 300 asec ≥10 fs envelope	≤1 μJ	$<10^{14}$ W/cm^2
Surface HOHG (current)	10s of eV - few keV	~ 900 asec ~40 fs envelope	≤1 μJ	$<10^{12}$ W/cm^2
Surface HOHG (future, i.e., ELI)	10s of eV - few keV	100-5 asec	≤ 100 mJ**	$<10^{23}$ W/cm^2 **

** Predictions based on PIC simulations.

Research on the generation of shorter pulse may be sub-attosecond uv and x-ray radiation using high harmonic generation from solids or frequency shifting and pulse shortening using the relativistic mirror concept will be performed with ultraintense laser part in the beam line section and or ultra-high intensity part of ELI.

Several specific features of the ELI-Attosecond beamlines and sources that were mentioned include:

1. Fs- and sub-fs-time structure of emitted radiation

2. Perfect optical synchronization between the driving laser pulse and the HH pulse allowing

pump-probe type of investigations

3. kHz repetition rates
4. approaching Joule energy level at single shots (low repetition rates)
5. sub-as time scales with the ultra-intense ELI driver

Among the potential applications that were mentioned experiments are:

- Multiple ionization/excitation of atoms and ions in XUV short fields [31]
- Attosecond nanoplasmonics [32]
- Attosecond science in condensed matter
- Imaging with ultrashort light pulses [27]
- Tailored electron dynamics and application to chemistry [33]

The planned experiments suggested to utilize the mentioned above specific features of ELI´s Attosecond beamlines and therefore should allow for complementary investigations performed at x-FEL facilities.

The comparison and relative merits and thus possible complementary role sharing may be understood by the following consideration. Xfels should be able to provide attosecond X-ray pulses at photon energies above a few keV. It might eventually be possible to generate sub-fs pulses also at lower photon energies by playing tricks with energy chirped electron bunches and optical compression, but I think this is far away. A typical pulse duration at 12 keV would be 300 attoseconds with about 10^9 to 10^{10} photons per pulse. These characteristics may not be sufficient for studying electron dynamics in atoms or molecules. ELI, in contrast, should be able to produce much more intense, broad-band pulses with durations well below 100 as and even below 5 as at photon energies between ~20–1000 eV. Such beams would be ideal for the study of electron dynamics.

It is not clear to us how many experimental stations with which characteristics could be envisaged at ELI. It is therefore difficult to judge how much of the rather broad science program could be pursued over a certain time. If it comes to setting priorities, for the part "Laser-produced X-ray beam" it should be carefully compared with existing synchrotron and Xfel facilities and only those parts should be pursued which clearly exceed the existing X-ray sources.

We recommend that ELI attosecond science not only be characterized in its own merit, but also be complimentarily compared with Xfel and given shaper focus on its competitive edges in whatever regimes or physics regimes in the backdrop of Xfel.

There was a suggestion that the elevated higher frequency photons thus produced can be a powerful tool for basic science such as to explore vacuum physics, as will be discussed in Subsec. 4. QED effects become accessible when the laser intensity reaches an appreciable fraction of the critical field (or Schwinger Limit [34]). Thus the intensities estimated for effects to observable vary from 10^{24} Wcm^{-2} for vacuum polarization to around 10^{29} Wcm^{-2} for pair production from the vacuum. While the lower limit of these intensities is thought to become accessible with the full ELI beam the experimental observation of vacuum polarization effects is still extremely challenging, since the effects are so small that they can only be detected with a temporally and spatially overlapping X-ray probe. Reaching the QED regime is made substantially easier by exploiting the extreme intensities predicted to be achievable in the primary focus of relativistic surface harmonics: Here the peak intensity can be as much as $n^{4/3}$ times higher than the initial laser intensity [35]. For 10^4 harmonics this corresponds to an intensity enhancement of $>10^5$ or peak intensities in excess of 10^{31} Wcm^{-2} far in excess of the Schwinger limit. In other words, imaging the e^+e^- pairs produced in the secondary focus (i.e. the harmonic focus) provides a highly promising platform for tests of QED. For effects such as vacuum polarization expected to be observable far below threshold, harmonic sources have the additional advantage intrinsically overcoming the most extreme experimental challenge – achieving the spatio-temporal overlap of probe and high field region: The highest harmonics can themselves be used to probe this intense region and are naturally co-propagating – hence allowing powerful measurements of QED effects in the coherent harmonic focus.

With regard to the attosecond science pillar, we recommend that ELI Management and scientific community to carve out the unique strengths that are derived from the ELI class. (We understand that while ELI is the highest intensity machine, it also affords substantial energy of the laser at kHz repetition rates. In another word it serves both the intensity frontier as well as the high repetition front.) It is also important that they carve out the differences between Xfel and ELI-driven X-rays. We would imagine examples such as studies on the dynamical behavior of atoms, clusters, and molecules, using attosecond pump and probe techniques with the ELI attosecond bay. We would like to see both complementary capabilities by these approaches, as well as competitive aspects. It would be good to cultivate the scientific user community in a concerted fashion.

2. Laser Acceleration

It is true that the birth place of high field science is the advent of scientific inquiry of laser acceleration and high field science still thrives in advancing laser acceleration research. The high intensity laser is near synonymous with brilliant ultrafast bursts of high energy beams of electrons, photons, and ions. With ELI entering into the ultrarelativistic regime of intensity, we expect more emphatic of this trend to continue to develop.

The goal of the Grand Challenge of laser acceleration was set as 100 GeV electron laser wakefield acceleration [36]. This is coy and perhaps strategically wise. Due to the emergence of many PW-class systems, in the next few years, that will be used for demonstrating 10 GeV modules based on the progress [37], including GeV acceleration [38], ELI's focus should be on a demonstration of acceleration to 100 GeV. For this ELI is ideally suited [39]. Many world class labs with PW lasers may be able to reach 10 GeV electron acceleration in the near future. However, it will have a hard time to approach 100 GeV. Thus ELI and the rest of the world ultra intense laser labs can nicely cooperate to sharpen their overall skills and know-hows in a collaborative network in this development. On the other hand, this energy level could trigger significant interest from the high energy physics community and could be a vehicle for getting their involvement. In fact the ELI GC Group on Laser Acceleration discussed and came up with a credible scenario and unit module that may form the foundation toward a TeV collider that is based on laser acceleration [39,40] and potentially cheaper than the conventional technology. However, this deliberation is based on future anticipated extension of technology of lasers and others.

ELI will be >100 PW peak power with large laser energy (3 kJ). Thus this presents opportunities for not only high peak focal intensity but also for a large focal volume but with lower intensity interactions. The long focal length interaction station of ELI enables us to extend the scaling of particle acceleration in a nearly one-dimensional theoretical expectation that in fact has never been conclusively tested in latest lesser energy laser experiments. We note here that strongly focused contemporary laser acceleration experiments realize the bubble regime of wakefield acceleration, which causes the break of wakefield via three dimensional dynamics and self-injection of electrons into the wakefield and subsequent sweep of trapped electrons to near monoenergetic accelerated energy spectrum. While this self-injection is a handy way for many applications, it may not be a desired way to operate high energy acceleration of electrons. For the latter purpose, we rather need to avoid self-trapping and the coherent wakefield without break and with weak transverse focus to avoid transverse emittance blowup. All these requirements for high energy acceleration of electrons point toward a near linear one-dimensional wakefield acceleration operation. Such an operation would also ameliorate the difficulty of accelerating positrons in the wakefield. ELI in fact rightly provides such a testbed nicely.

It should be commended that ELI plans a high energy beams facility and the high intensity beamlines with higher repetition rate DPSSL lines as well as the capability to have multiple beamlines by as many as 10 BL. These allow experiments with relatively high fluence of beams as well as staged acceleration toward high energies, such as 10 stages of a 10 GeV acceleration unit. Such a facility will provide a wealth of data for the future high energy accelerators. It is noted that such data probably does not include those for high enough luminosity for a future collider. For a collider it is necessary to have ever increasing luminosity for higher energies of the collider. Thus it is of paramount importance to bring in an extremely high fluence laser driver with high enough efficiency for this to qualify for a collider driver. Such should be left for another class of investigation, such as a high fluence fiber laser and a large aperture ceramic laser.

As noted above, since ELI provides highest laser energy for an ultrashort pulse laser, this serves to test the highest energy generation by laser acceleration. Unlike the contemporary experiments at relatively high plasma density, this high energy capability of ELI allows for experiments with less density and thus higher energy gain with a nearly one-dimensional laser focus. The acceleration of more than TeV electrons with ELI seems quite possible in one stage at lower density than contemporary experiments. This should pave a way to investigate the scaling of the future path in terms of the energy frontier. If the current theoretical scaling of the electron energy to scale to the inverse of the electron density and proportional to the laser intensity does hold in higher intensity (greater than 10^{20} W/cm^2) and lower density plasma (less than 10^{17}/cm^3), we can now foresee an ultrahigh energy frontier by laser acceleration. If in fact this scaling holds, one could estimate that a laser with some 20 MJ with a ps pulse length could drive electrons in wakefields toward PeV over km. Thus ELI could provide a valuable peek into the PeV frontier [9].

Even though ELI will not have us reach PeV, it stimulates us to imagine how a non-collider paradigm in the future in extreme high energies might look like. One of the interesting physics objectives is the study of the Space-Time structure using high energy photons. The foamy structure of the space and time may introduce the energy dependent light velocity in the quantum gravity and string theories, something like, $V = c\ (1 - \xi_1 E/E_{QG} - \xi_2 (E/E_{QG})^2)$ [13]. The first term coefficient ξ_1 is an order of one. E_{QG} is usually assumed as an order of the Planck Mass ($\sim 10^{28}$ eV). This effect becomes more significant as a function of the energy of photons. In case of ELI, the back of envelope calculation shows the time delay of photons due to the propagation inside the foamy space-time, $\Delta T/(1\ \text{attosecond}) \sim (L/1\ \text{km})*(E/3000\ \text{TeV})$. To achieve the measurement of this effect, it requires particle acceleration up to ~ PeV, and a technology to measure attosecond timing. However, it will give us an opportunity to access the Planck-Mass scale space-time structure. In the field of high energy gamma ray astronomy, there are several results on the energy scale of E_{QG} using the rays of 10 GeV–1000 GeV from distant sources (typically the propagation distance is $L = 10^{16\text{-}17}$ m). The best limits so far obtained are about 3–10% of the Planck Mass. It is recommended to make an entry effort in increasing the maximum energy in the particle acceleration as high as possible step by step, as there may be quite a different world waiting for us even if the accelerated particles may be of a very small amount. However, there is a recent report that sets the limit higher [41]. The Landau-Pomeranchuk-Migdal (LPM) effect [42] has been known for years, which is the modification of the interaction of photons and electrons within high density matter. The electromagnetic interaction can be described by the Bethe-Heitler formula in a low energy regime. If the energies of electrons and photons become higher, the matter density looks denser for electrons and photons due to the relativistic contraction. The critical energy can be defined, where the mean free path of Coulomb scattering in the matter becomes equal to the Compton wavelength of electrons. The interference by Coulomb scattering modifies the pair creation and the Bremsstrahlung differential cross-section. For examples, the differential cross sections of pair creation and Bremsstrahlung are significantly modified above 1–10 TeV energy inside the lead material (this effect at an entry was measured by Klein et al. at SLAC in 1990s in the Bremsstrahlung channel) [43].

The ELI's ultrarelativistic feature introduces the dynamics of protons to behave similarly to electrons in the intense laser fields. Because of this feature, it is now possible that an intense laser pulse from ELI beyond intensity 10^{24} W/cm^2 (certainly at 10^{25} W/cm^2) can drive protons to high energies just like electrons are driven by the laser wakefields beyond 10^{18} W/cm^2. The energy gain scaling in this regime is proportional to the laser intensity and since accelerated protons move together with the laser pulse (i.e just like a piston), the energy gain is adiabatic and thus the energy spectrum is monoenergetic [5,44]. It is thus possible to quickly boost the proton energy in this regime by a relatively small increment of intensity and more predictively. In this ultrarelativistic regime while laser electron acceleration may become less ideal, laser proton acceleration becomes more ideal. It may be possible to construct a 'collider' of ion beams that are driven by opposing two ultrarelativistic laser pulses. Likewise, the radiative friction on electrons, one of the quantum effects in ultrarelativistic regimes, becomes significant, which allows to emit gamma-rays very copiously and effectively [45,46]. At laser intensities of 10^{22} W/cm^2 and beyond an electron acquires such high velocities that the time for an emitted photon to escape from the vicinity of its source becomes non-negligibly small anymore. As a consequence, reabsorption of such photons becomes possible and may be detected via the modified electron trajectories or a red shift of the emitted spectrum when observing perpendicular to the laser propagation direction [46]. This would be one of suite of various high energy gamma-rays that we can harness from ELI (another prominent one is the laser Compton backscattered gamma-rays, which will be discussed in depth in Subsec. 3).

The most attractive and fundamental characteristics of the ELI facility is that its suite of beams, as were just mentioned above, come in perfect synchronism with its optical pulses themselves. Thus all the high energy beams (electrons, ions, gamma-rays) are synchronous with each other and with the optical beam, and its structure is typically the one of ultrafast bunches. This provides a basis for arranging a marriage between different beams to collide or influence each other. An example may be a set of an intense optical beam that counterpropagates against the laser accelerated high energy electron bunch. Such may be a useful setup for exploring the highly nonlinear QED effects, as will be discussed in Subsec. 4.

By means of Doppler shifting, e.g. via colliding beams or accelerators, both the electric field and frequency can be enhanced for pair production or vacuum polarisation.

An application of laser acceleration to the electron-positron pair creation by laser-accelerated electrons colliding with an intense laser beam [47] is suggested.

- Setup 1

Produce a beam of 10^{10} electrons of 5 GeV energy via plasma wakefield acceleration and let it collide with a laser pulse of 10^{22} W/cm^2 intensity, focal diameter about 10 microns (= 10 PW), 100 fs duration, (= 1 kJ total energy). Then around 10^9 electron-positron pairs are generated per shot (perfect beam overlap assumed). A high rep-rate is not material.

Note: The experiment would be an all-optical realization of the well-known SLAC experiment by Burke et al. [48], but probing a different regime of interaction: At SLAC the normalized vector potential was $\xi \ll 1$, whereas here it is $\xi \gg 1$ and the laser field strength in the projectile frame is close to the critical value so that the process proceeds at the borderline between tunneling and "over-barrier" pair creation.

- Setup 2

Electron-positron pair creation by relativistic proton impact on an intense laser beam (similar to Setup 1 but realizing another pair production channel due to the large projectile mass: the nonlinear Bethe-Heitler process, which has not been observed yet). Two alternative scenarios are conceivable [49]:

a) *Tunneling regime:* Employ 50 GeV proton beam (Lorentz factor of γ=50), containing about 10^{12} particles, which might be produced either by conventional acceleration techniques or by laser acceleration in the piston regime [6]. Collision with a laser pulse of 10^{24} W/cm^2, 5 microns spot size, 20 fs duration (total energy = 5 kJ) produces about one electron-positron pairs per shot. At 10^{26} W/cm^2 the yield increases to 10^{10} pairs.

b) *Few-photon regime:* Utilize the same proton beam and let it collide with an X-ray pulse produced from plasma harmonics (say 9 keV photon energy). This way, about one Bethe-Heitler pair can be generated per shot via two-photon absorption, assuming an X-ray intensity of 10^{20} W/cm^2 and 10 fs pulse duration. The yield is proportional to the square of the X-ray intensity. Also the bound-free pair creation channel, where the electron is produced in a low-lying bound state of the projectile, is accessible via two-photon absorption.

Note: Alternatively, these multiphoton processes could be realized with the ELI attosecond beam (of 100 eV) when combined with an ultrarelativistic nuclear beam of γ =3500 as available at the LHC at CERN. Furthermore, when the LHC proton beam is collided with the harmonic X-ray pulse, even nonlinear Bethe-Heitler production of muon-antimuon pairs could be realized [50]. Indirect production of muon pairs through electron-positron generation in ultrarelativistic laser-nucleus collisions (as described in Setup 2a) has been proposed in [51].

- Setup 3

Purely light-induced electron-positron pair creation in the field of two counterpropagating laser pulses:

An intriguing process of QED is the generation of electron-positron pairs from vacuum in the presence of superintense photon fields, which may occur in the combined field of two counterpropagating strong laser beams. The threshold of observability of this process is reached when the pulses have an intensity of 2 x 10^{26} W/cm^2. Then, assuming a focal area close to the diffraction limit and 10 fs pulse duration, about one pair is generated per shot [52]. It is interesting and encouraging that the required value of the laser intensity is significantly smaller than the Schwinger limit. It will, however, be crucial to reach this threshold intensity – which lies at the upper border of the capability of ELI – because at half the intensity, for example, the pair yield drops down by 9 orders of magnitude due to the exponential field dependence of this tunneling process [52]. Superposition of a high-frequency field component might exert an auxiliary influence on the production process [53]. We note moreover that a very pure vacuum in the beam crossing area will be required, since even a small amount of background electrons would give rise to prolific pair creation by the reaction described in Setup 1, as was shown recently in [54].

Here we will not further get into listing all the above combinations, but it is already clear that ELI can enjoy various imaginative marriages of these combinations. This is a completely unique aspect of ELI absent in a conventional accelerator facility. We recommend an appropriate experimental allowance for such should be prepared.

Having said this, it is quite important that the ELI laser accelerator facility and research be closely collaborating with the conventional accelerator community. The level of sophistication and the long years of experiences that the accelerator physics community has pioneered and accumulated are among the most spectacular technologies that last 100 years of human history have witnessed. In this regard, it is encouraging that ICUIL and ICFA have agreed to collaborate in jointly promote the investigation into the possibility of future accelerators based on lasers since this January 2009 [55]. On one hand, the ultra intense laser community has more at stake in the collaboration, so that the initiative and overture by the laser acceleration community to the conventional accelerator community should be encouraged with various channels, including the above. This we recommend. Perhaps, this joint effort could make a complementary science program that are mutually fruitful, and/or some joint efforts that could stimulate the research development that may not be achieved without such collaboration. We recommend that at ELI this cross-fertilization of two scientific disciplines (and cultures) should be forged and nurtured.

As mentioned before, it will become quite important in this facility not only accelerate charged particles to high energies in compact fashion, but also safely and compactly decelerate them in order to reduce radioactivations within a manageable space of the ELI infrastructure. A collective deceleration technique that is generically common with the laser acceleration technique might be valuable here [19].

3. Photonuclear Physics

Methods to produce monoenergetic directed brilliant pulsed gamma-rays have been already discussed earlier in Subsecs.[a] and [b]. The principal approach is to utilize the intense laser backscattered on a high energy electron bunch to produce such gamma-rays by the Compton backscattering process. This method is proven and has been already employed by several laboratories around the world to produce some promising results in exploring nuclei by high energy photons. In this technique, for example, a large amount of MeV gamma-rays with the above characteristics may be generated. MeV is the energy range where typical nuclear reactions and nuclear excitations take place. We may reminisce the invigorated re-birth of atomic physics right after the birth of the laser, which provided coherent directed, monoenergetic directed pulsed eV photons and contributed to the revolutionary development of the study of the atomic structure, spectroscopy, accurate account of its dynamics, and control of atoms and their dynamics. Nonlinear optics was soon borne. We may expect a somewhat parallel and equally exciting dynamic development, if and when such gamma-ray photon sources at the MeV scale become available for the exploration of nuclei, their spectroscopy and identification, manipulations, and eventual control of them. This vision may be called photonuclear physics. The ELI GC has wisely chosen this area as one of four Grand Challenges, and we highly applaud this vision. This is the area that ELI can make a breakthrough in a unique way. Other photon sources, such as conventional synchrotron radiation sources precipitate in its brightness beyond 100 keV, where the laser Compton gamma-rays pick up its brightness encompassing well beyond MeV, perhaps in proportion to the square of the electron Lorentz factor γ, because of its kinematics. Electron bunches may be provided by an adjacently installed conventional linac, or by ELI generated laser-accelerated electron bunches (see Subsec. 2). We anticipate that this area is so nearly virgin that any substantial effort such as at ELI can make a total breakthrough and breakaway from the past attainment of science.

The interaction of photons with hadrons at high energies (hadronic feature of photons) is also an interesting and important topic. Especially the measurement of the photo-pion production cross section as a function of energy is interesting. There was an intensive measurement on photo-pion production by a HERA experiment at lower energy (e-p collider) at DESY, but we can use higher energy photons (not electrons).

We need some investigations how much ELI can contribute to the high energy hadron physics.

The nuclear resonance fluorescence is typical photonuclear reaction that may be best explored by the ELI driven new light source at MeV. With the previously described ELI sources of coherent high-frequency pulses also electric dipole transitions in nuclei are feasible [56]. A moderate pre-acceleration of the ions would be of assistance here since it increases the number of accessible isotopes. It is interesting to note that certain electric quadrupole (E2) or magnetic dipole (M1) transitions can be competitive in strength with E1 transitions [57]. Resonant direct interactions of laser radiation with nuclei would pave the way to nuclear quantum optics. The beams reflected from relativistic dense electron sheets allow for an easy switching of the polarization by switching the polarization of the primary reflected laser beam. This switching between rather pure polarizations can be the basis for further interesting nuclear fluorescence studies.

A series of experiments has been performed at synchrotron radiation facilities [58], studying the parity non-conservation in nuclear resonance fluorescence from nuclei having close-lying parity-doublet states. According to first order perturbation theory calculations, the measured asymmetry is strongly enhanced, because the parity violating matrix element is divided by the small energy difference of the two levels of opposite parity. Here many nuclei with a possible E1/M1 mixing have been investigated (^{18}F (1080 keV); ^{19}F (109.9 keV); ^{21}Ne (2789 keV); ^{175}Lu (396 keV), but experimental accuracies were insufficient. Thus for ^{21}Ne the level distance between the $1/2^+$ and $1/2^-$ states is only 5.7 keV, leading to a large enhancement effect. Here the Seattle group reported an asymmetry of $(0.8\pm1.4)\cdot10^{-3}$ [59]. With the new brilliant γ beams from ELI the situation may improve. In this way elementary parity-violating meson-nucleon coupling constants can be determined [58,60–62].

The potential of NRF applications is quite impressive. Typically photonuclear resonances will have extremely small line widths, broadened by the thermal Doppler shift with: $\Delta E/E \sim 10^{-6}\sqrt{(kT/25meV)\cdot(240/A)}$. In order to detect the narrow resonances with high sensitivity a 'notch' detector technique can be applied, where the presence of a given sample material is detected via the absence of its corresponding resonance fluorescence photons from a reference sample made of the material of interest [63–65]. A γ beam with narrow energy width, including the resonance energy of interest, is passed through a sample. If present, the isotope of interest will burn an extremely narrow hole (‘notch’) into the γ beam by scattering out the resonance photons. This depletion of resonance photons – called 'notch' – is detected by placing an additional probe of the expected isotope into the beam with the notch and measuring the resonance scattering together with the off-resonance photons. In this way a depletion of the resonance line due to the sample is detected, using the very high resolution of nuclear resonance scattering. Here the new brilliant, polarized, high-energy γ beams are very useful, because they penetrate thick samples and allow for the detection of very small amounts of isotopes. This method has been proposed to detect e.g. ^{235}U, ^{239}Pu [64] or relevant isotopes of nuclear waste, but also for the detection of clandestine nuclear materials [66]. The nuclear resonance fluorescence scattered sideways can be measured with a high-purity Ge detector to study radioactive waste drums non-intrusively [64]. The sensitivity of detecting the U and Pu waste is improved using M1 transitions due to the directional orientation of the decay photons after the nuclear fluorescence with polarized beams.

Other experimental examples discussed were:

- Coherent nuclear excitations [67,68];
- Time-resolved nuclear decay studies [69];
- Production of brilliant micron neutron beams [69–71];
- Field-induced phenomena at the atomic-nuclear physics interface [72–77].

For example, in studying time-dependent nuclear processes we can transform the well-established attosecond science technique of streaking technique of atomic physics [78,79] into the nuclear energy relevant regime. Here the so-called streaking method in zs time scales of electrons and protons have been discussed.

There are many other ways to generate MeV gamma-photons that have been suggested during the GC meeting. These include a scheme to generate brilliant photon pulses extending from the keV- to multi-MeV photon energies [80]. This will rely on the Thomson backscattering of photons with initial energy E_i on highly dense electron bunches driven out of ultrathin foils of thicknesses of a few to tens of nm thickness by a driver laser. This method could achieve even higher brightness than the laser Compton process, because photons are generated from solid density targets and highly compressed by laser acceleration of these thin targets.

The following table summarizes the various experimental perspectives for photonuclear physics with ELI. The table also includes the corresponding laser parameters required to perform the respective experiments. For each case the focal spot size (and thus the laser intensity) has been derived from the normalized laser amplitude a_d required to generate the requested photon energy

Physics	γ energy [eV]	laser energy [J]	laser intensity [W/cm^2]	Pulse width [fs]	Focal spot [μm]	rep. rate [1/s]
Coherent excitations	10^4–10^5	500	>$3\cdot10^{18}$	10	~100–150	max.
NRF	10^5–$5\cdot10^6$	500	> 10^{20}	10	~30–100	max.
LINF	—	500	$3\cdot10^{24}$ – $3\cdot10^{25}$	10	1	max.
Nuclear decay times	10^5–10^7	500	> 10^{20}	10	~30–150	max.
Neutron beams	~ $6\cdot10^6$	500	>$1.5\cdot10^{21}$	10	~40	max.

4. Vacuum Physics

It may be said that the understanding of vacuum has become one of the most important issues of fundamental physics today. This is exemplified by the critical problem of dark energy in cosmology, which shows how little we know about vacuum. The typical contemporary approach of fundamental physics has been to take accelerated charged particles with large momenta that have proportionally smaller spatial ability to resolve (via the Heisenberg's uncertainly principle) that probe the minute constituents that comprise minute aspects and structure of matter and fields. Since fields are represented by particles, this is the main stay of high energy particle physics and its most sophisticated contemporary tool of colliders. However, in addition to what we discussed in Subsec. V.2, what ELI can open up as a new horizon is to introduce a way to explore the vacuum (and other fields) with the greatest amplitude of fields with zero (or near zero) momenta. In contrast in the collider paradigm the amplitude merely corresponds to a single particle (i.e. to a near zero amplitude approach). If we have very large momenta of passing colliding particles, a near zero momentum phenomenon such as the possible constituent of 'dark energy' (or even a 'light mass' candidate of 'dark mass'), if it turns out to be the case, may be obscured by such noise [5].

ELI can serve as the first conscious scientific step towards the understanding of quantum vacuum. In this regard, the ELI Ultra High Field Science should not be limited to the "boiling vacuum" where e^+e^- pairs can be spontaneously created from the vacuum under extremely intense fields, however important this may be. Instead, additional novel aspects of probing quantum vacuum should be encouraged. The presently listed three pillars are appropriate, while the Attosecond Sciences cover the laser temporal frontier and the High Energy Beam facility pushes the envelope of the energy frontier, the Ultra High Field Sciences relates to the laser intensity (or amplitude) frontier. For example, the probing of the event horizon, or the Hawking-Unruh effect [81–83], can be associated with the Ultra High Field Sciences, while the "cosmic accelerator" [84], that is the acceleration mechanism for ultra high energy cosmic rays (UHECR), can be part of the High energy Beam Facility program. However, artificial boundaries may be of little use, as for example, as discussed in Subsec. 2, if we can accelerate even a small amount of ultrahigh energy particles, such can explore the texture of vacuum at the high energy end.

Because of the novel approach to the fundamental physics, many committee members felt that vacuum physics is one of the most exemplary Grand Challenges among the four GCs. The major issues not addressed during the presentations, however, were specific requirements on the laser and the experimental systems. In particular, it would seem that vacuum interactions will place rather stringent requirements on the vacuum and associated diagnostics, e.g. will signals be masked by background ion signals from material ionized outside of the main focus ? As is customary, the signal-to-the-noise ratio is the most important key to realize the promise into reality. Thus we find that this is a high risk high return pillar.

QED effects become accessible when the laser intensity reaches an appreciable fraction of the critical field (or Schwinger Limit). Thus the intensities estimated for effects to observable vary from 10^{24}Wcm^{-2} for vacuum polarization to around 10^{29} Wcm^{-2} for pair production from the vacuum [85].

While the lower limit of these intensities is thought to become accessible with the full ELI beam, the experimental observation of vacuum polarization effects is still extremely challenging, since the effects are so small that they can only be detected with a temporally and spatially overlapping X-ray probe (the depolarization of optical light can also in principle be observed, see Setup 2 in the paragraph below on diffraction effects in laser-laser collision). Combining the bunch of accelerated high energy electrons (either by a conventional electron linac or laser accelerated electrons), the effective field intensity may be enhanced by γ^2 over the original optical beam intensity seen by the electron bunch. A pioneering experiment carried out at SLAC in 1990's [48] was with the dimensionless parameter $\chi = E / E_{cr} \sim 0.3$ barely into the entry of Schwinger nonperturbative regime (while a_0 is merely ~ 0.3), though apparently it was in fact into the nonperturbative entry, contrary to the experimentalists' belief. (A recent article [86] by Reiss shines an invaluable light on interpreting this physics, in which he draws close parallels with the above field ionization of multiple electrons from an atom near the Keldysh threshold that may not be described by perturbation theory).

Another important aspect of vacuum physics was touched by Heinzl (and a paper by Shore) [87]. It is pointed out that the near Schwinger amplitude a large amount of photons are absorbed by vacuum to distort it. This should correspond to the emergence of the imaginary part of the dielectric function. Through the Kramers-Kronig relation, this means that the intense fields amount to change the real part of the dielectric function. The real part change amounts to a dispersion of light in vacuum. Thus I surmise that the speed of light near the Schwinger field is in fact different from the small amplitude value of the speed of light! We will be facing a very important phenomenon of variable propagation of speed of light at or near the critical field, another important implication and exploration of special theory of relativity at the amplitude frontier.

In Subsec. V.1 we already mentioned the application of HHG attosecond X-rays to reach the Schwinger field, not by the original optical field itself.

A couple of examples of detail are explained here. First, diffraction effects in laser-laser collision have been considered by several groups. Due to quantum vacuum polarization effects (VPEs) a strong laser beam can change the polarization of a probe field that passes through it (see **FIGURE 1**) [88].

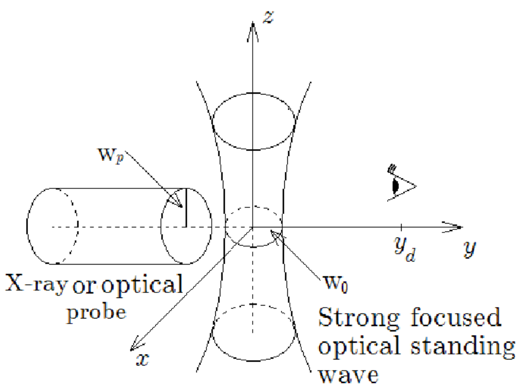

FIGURE 1: Schematic setup for observing light-by-light diffraction.

- Setup 1

The strong field has the following parameters: wavelength λ_0=0.745 μm, spot radius w_0=5 μm and intensity $I_0=10^{25}$ W/cm^2. The probe beam is an X-ray probe with wavelength λ_p=0.4 nm and waist size w_p=8 μm. The probe acquires an ellipticity of the order of 10^{-5} rad. Such values of ellipticity and polarization are nowadays measureable in the X-ray regime [89].

- Setup 2

The strong field parameters are the same as before but the probe field is optical: wavelength λ_p=0.745 μm and waist size w_p=300 μm. In this case values of ellipticities of the order of 10^{-10}-10^{-9} rad are obtained that, again, can be measured nowadays [90].

Note: As compared to estimations within a plane-wave approximation, the diffraction effects due to the spatial confinement of the strong laser beam decrease the ellipticity of the probe by an order of magnitude and induce a rotation of the polarization main axis of the same order of the ellipticity.

Second, laser photon merging in proton-laser collision is considered. In the head-on collision of a high-energy proton and a strong laser beam photons from the laser merge into one high-energy photon by interacting with the electromagnetic field of the proton (see **FIGURE 2**) [91].

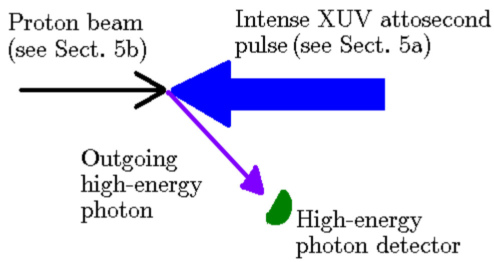

FIGURE 2: Schematic setup for observing laser photon merging.

- Setup 3

The proton beam parameters are [6]: proton energy E_p = 50 GeV, number of protons per beam 2 × 10^{12}, beam transversal radius 5 μm and beam duration 20 fs. Rather high laser photon energies are needed to suppress background processes and the strong XUV attosecond pulses discussed in [4] are suitable here. By extrapolating the results of the simulations in [26] it can be envisaged that strong XUV attosecond pulses with the following characteristics can be produced by the reflection of an ultra-strong laser pulse (intensity of 3 × 10^{24} W/cm^2, spot-radius of 5 μm and duration of 5 fs) from a plasma surface: intensity of 1.5 × 10^{24} W/cm^2, photon energy of 200 eV, pulse duration of 40 as. An energy conversion efficiency of 4 × 10^{-3} is assumed. With these parameters about five photons per shot are produced due to laser photon merging.

Note 1: the simulations performed in [4,6] have been carried out for laser intensities much smaller than those available at ELI. If the results can be scaled to intensities of the order of 10^{25} W/cm^2 like those available at ELI, much larger rates can easily be obtained and one can even expect that non-perturbative, multiphoton (merging of more than two laser photons) VPEs could be observable.

Note 2: if ELI could be combined with a large-scale proton accelerator much higher photon yields can be obtained.

VI. CONCLUSIONS

ELI is expected to serve as a unique discovery machine that no other facility has a parallel to it. Its scientific promise has been reviewed in the above in some detail. This facility has a broad scientific outreach, not simply restricted to a single grand challenge task, but touches on a variety of layered scientific fundamental questions ranging from feeling the texture of vacuum, extending the energy frontier, manipulating nuclei, and observing the dynamics of nanometric nature in attosecond accuracy, including the biomolecular dynamics to unlock the secret of life in action. With so much exciting possibilities pregnant we anticipate ELI to spawn out a new era of science.

We in the 21st Century society are left with difficult problems that cannot be easily solved by the extension of the methods the 20th Century science has amassed. Or shall we even say that we ourselves are tangled up in the web of the very problems that need to be addressed with a fresh perspective and / or new way of doing. The promise of ELI just might live up to such a demand, we shall see. In this regard it is important to keeping in mind its possible impact on contemporary societal applications.

Some of the societal applications that ELI may bring out or impact on would include: affordable compact cancer therapy facilities driven by lasers, brilliant molecular imaging technique of tumors and other irregularities, nuclei detection and manipulation, systematic chemicals and drug development based on the knowledge of molecular dynamics in addition to its structure, to name a few. In addition, the science and the development of this supersophisticated laser system will spin off a suite of vigorous laser technology companies.

The broad science coverage and yet not too large-scale of the facility of ELI may help excite the public to renew their curiosity of the nature together with scientists so that perhaps it might bring the frontier science once again closer to the public. This way ELI might help the broken-down specialization of contemporary science once again move toward more of integration than more of division: Would this be too much to imagine?

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REFERENCES

1. G. Mourou, ICUIL lecture (Cassis, 2006).
2. F. Krausz and M. Ivanov, *Rev. Mod. Phys.* **81**, 163 (2009).
3. M. Hentschel et al., *Nature* **414**, 509 (2001).
4. G. Tsakiris et al., *New. J. Phys.* **8**, 19 (2006).
5. T. Tajima, *Eur. J. Phys.* **D**, e2009-00107-8 (2009).
6. T. Esirkepov et al., *Phys. Rev. Lett.* **92**, 175003 (2004).
7. R. Schoenlein et al., *Science* **287**, 2237 (2000).
8. T. Nakano et al., *Phys. Rev. Lett.* **91**, 012002 (2003).
9. T. Tajima and G. Mourou, *Phys. Rev. ST AB* **5**, 031301 (2002).
10. A. Suzuki, ICFA Seminar (SLAC, Stanford, 2008).
11. G. Mourou et al., *Rev. Mod. Phys.* **78**, 1 (2006).
12. N. Arkani-Hamed et al., *Phys. Lett.* **B 429**, 263 (1998).
13. J. Ellis, *Nature* **393**, 763 (1998).
14. "ELI - Extreme Light Infrastructure Report of the Grand Challenges Meeting", Palaiseau, April 27-28, 2009, with written contribution from: E. Esarey, A. Di Piazza, H. Gies, K.Z. Hatsagortsyan, T. Heinzl, A. Ilderton, C.H. Keitel, M. Marklund, S.D. Moustaizis, C. Müller, N.B. Narozhny, I. Ploumistakis, R. Schützhold,D. Symes, I. Tsohantjis, D. Charambilidis, G. Tsakiris, P. Thirolf, T. Tajima, G. Korn, A. Bandrauk, C.P.J. Barty, D. Habs, J. Schreiber, and H.A. Weidenmüller, edited by G. Korn, (2009).
15. ELI site resolution (October, 2009).
16. A. Baltuska et al., *Opt. Lett.* **20**, 2174 (1995).
17. S. Payne et al., *J. Fusion En.* **17**, 213 (1998).
18. IAEA report 188 "Radiological Safety Aspects of the Operation of Electron Accelerators" (IAEA, Vienna, 1979).
19. H.C. Wu et al., submitted to *Phys. Rev. Lett.* (2009).
20. *Nature* **461**, 708 (2009).
21. L. Lompre, et al. AIP Proc. **206**, 277 (1990);
    P. Corkum, Phys. Rev. Lett. **71**, 1994 (1993).
22. T. Tajima, K. Mima, and H. Baldis, eds., *High Field Science*, Kluwer/Plenum, New York (2000).
23. S. Bulanov et al., *Plas. Phys.* **1**, 745 (1994).
24. A. Pirozhkov et al., *Phys. Lett.* **A 349**, 256 (2006).
25. S. Bulanov et al., *Phys. Rev. Lett.* **91**, 085001 (2003);
    M. Kando et al., *Phys. Rev. Lett.* **99**, 135001 (2007).
26. U. Teubner and P. Gibbon, *Rev. Mod. Phys.* **81**, 445 (2009).
27. R. Neutze et al., *Nature* **406**, 752 (2000);
    H. Chapman and J. Hajdu, *Nature Phys.* **2**, 839 (2006).
28. D. Charambilides, ELI Grand Challenge (ELI GC), Paris, 2009 (see Ref. 14).
29. Y. Nomura et al., *Nature Phys.* **5**, 124 (2009).
30. M. Zepf et al., *Plas. Phys. Cont. Fus.* **49**, B149 (2007).
31. H. Egger et al., *AIP Conf. Proc.* **119**, 64 (1984).
32. M. Stockman et al., *Nature Photonics* **1**, 539 (2007).
33. T. Pfeiffer et al., *Chem. Phys. Lett.* **463**, 11 (2008).
34. J. Schwinger, *Phys. Rev.* **82**, 664 (1951).
35. S. Gordienko, et al. Phys. Rev. Lett. **94**, 103903 (2005);
    R. Hoerlein et al., Eur. Phys. J. D **55**, 475 (2009).
36. T. Tajima and J. Dawson, *Phys. Rev. Lett.* **43**, 267 (1979).
37. J. Faure et al., *Nature* **431**, 541 (2004);
    C. Geddes et al., *Nature* **431**, 538 (2004) ;
    S. Mangles et al., *Nature* **431**, 535 (2004).
38. W. Leemans et al., *Nature Phys.* **2**, 696 (2006) ;
    N. Hafz, et al. *Nature Photon.***2**,571 (2008).
39. E. Esarey et al., *Rev. Mod. Phys.* **81**, 1229 (2009).
40. M. Xie et al., *AIP Proc.* **398**, 233 (1997).

41. A. Abdo et al., *Nature*, doi 10.1038/nature08574 (2009).
42. L. Landau and L. Pomeranchuk, *Dokl. Akad. Nauk SSSR* **92**, 535 (1953);
A. Migdal, *Phys. Rev.* **103**, 1811 (1956).
43. S. Klein, *Rev. Mod. Phys.* **71**, 1501 (1999).
44. T. Esirkepov et al., *Phys. Rev. Lett.* **89**, 175003 (2002).
45. A. Zhidkov et al., *Phys. Rev. Lett.* **88**, 185002 (2002).
46. C.H. Keitel et al., *J. Phys.* **B 31**, L35 (1998).
47. M. Ruf et al., *Phys. Rev. Lett.* **102**, 080402 (2009) ;
A. Di Piazza et al., *Phys. Rev. Lett.* **103**, 170403 (2009).
48. D. Burke et al., *Phys. Rev. Lett.* **76**, 1626 (1997).
49. C. Müller et al., *Phys. Rev.* **A 67**, 063407 (2003);
A.I. Milstein et al., *Phys. Rev.* **A 73**, 062106 (2006).
50. C. Müller et al., *Phys. Rev. Lett.* **101**, 060402 (2008);
C. Müller, *Phys. Lett.* **B 672**, 56 (2009).
51. M. Kuchiev, *Phys. Rev. Lett.* **99**, 130404 (2007).
52. S.S. Bulanov et al., *J. Exp. Theor. Phys.* **102**, 9 (2006).
53. R. Schützhold et al., *Phys. Rev. Lett.* **101**, 130404 (2008)
54. A.R. Bell and J.G. Kirk, *Phys. Rev. Lett.* **101**, 200403 (2008).
55. ICUIL HP: http://www.icuil.org/
56. T.J. Bürvenich, J. Evers and C.H. Keitel, *Phys. Rev. Lett.* **96**, 142501 (2006).
57. A. Palffy, J. Evers, and C.H. Keitel, *Phys. Rev.* **C 77**, 044602 (2008).
58. A.I. Titov, M. Fujiwara and K. Kawase, *J. Phys.* **G 32**, 1097 (2006).
59. E.D. Earle et al., *Nucl. Phys.* **A 339**, 221c (1983).
60. W.C. Haxton et al., *Phys. Rev. Lett.* **86**, 5247 (2001).
61. W.C. Haxton et al., *Phys. Rev.* **C 65**, 045502 (2003).
62. E.G. Adelberger et al., *Ann. Rev. Nucl. Part. Sci.* **35**, 501 (1985).
63. W. Bertozzi et al., *Nucl. Instr. Meth.* **B 241**, 820 (2005).
64. W. Bertozzi et al., *Phys. Rev.* **C 78**, 041601(R) (2008).
65. J. Pruet et al., *J. Appl. Phys.* **99**, 123102 (2006).
66. R. Hajima et al., *Nucl. Instr. Meth.* **A 608**, Suppl. 1, S57 (2009);
N. Kikuzawa et al., APEX **2**, 036502 (2009).
67. G. Smirnov et al., *Phys. Rev.* **A 71**, 023804 (2005).
68. J. Hannon et al., *Hyperf. Int.* **123/124**, 127 (1999).
69. D. Habs et al., *Eur. Phys. J.* **D 55**, 279 (2009).
70. P. Böni, *Nucl. Instr. Meth.* **A 586**, 1 (2008).
71. C. Schanzer et al., *Nucl. Instr. Meth.* **529**, 63 (2004).
72. A. Shabaz et al., *Phys. Rev. Lett.* **98**, 263901 (2007).
73. M. Casu and C.H. Keitel, *Europhys. Lett.* **58**, 496 (2002).
74. S. Chelkowski et al., *Phys. Rev. Lett.* **93**, 083602 (2004).
75. N. Milosevic et al., *Phys. Rev. Lett.* **92**, 013002 (2004).
76. G.R. Mocken and C.H. Keitel, *J. Phys.* **B 37**, L275 (2004).
77. A. Korney and B. Zon, *Laser Phys. Lett.* **4**, 588 (2007).
78. J. Itatani et al., *Phys. Rev. Lett.* **88**, 173903 (2002).
79. R. Kienberger et al., *Nature* **427**, 817 (2004).
80. D. Habs et al., *Appl. Phys.* **B 93**, 349 (2008).
81. S. Hawking, *Comm. Math. Phys.* **43**, 194 (1975).
82. W. Unruh, *Phys. Rev.* **D 14**, 870 (1976).
83. P. Chen and T. Tajima, *Phys. Rev. Lett.* **83**, 256 (1999).
84. Y. Takahashi et al., in *High Field Science*, eds. T. Tajima, K. Mima and H. Baldis, Kluwer/Plenum, NY, 2000.
85. R. Schützhold et al., *Phys. Rev. Lett.* **103**, 170502 (2009).
86. H. Reiss, *Eur. Phys. J.* **D**, DOI:10/1140/epjd/e2009-00039-3(2009).
87. G. Shore, *Nucl. Phys.* **B 778**, 219 (2007).
88. A. Di Piazza, K.Z. Hatsagortsyan and C.H. Keitel, *Phys. Rev. Lett.* **97**, 083603 (2006).
89. E.E. Alp, W. Sturhahn, and T.S. Toellner, *Hyperfine Interact.* **125**, 45 (2000).

90. K. Muroo, et al., *J. Opt. Soc. Am.* **B 20**, 2249 (2003).
91. A. Di Piazza, K.Z. Hatsagortsyan and C.H. Keitel, *Phys. Rev. Lett.* **100**, 010403 (2008);
A. Di Piazza, K.Z. Hatsagortsyan and C.H. Keitel, *Phys. Rev.* **A 78**, 062109 (2008).