Eur. Phys. J. D (2009)
DOI: 10.1140/epjd/e2009-00107-8

THE EUROPEAN
PHYSICAL JOURNAL D

Regular Article

Prospect for extreme field science

T. Tajima[1,2,a]

[1] Ludwig Maximilian University and Max Planck Institute for Quantum Optics, 84578 Garching, Germany
[2] Japan Atomic Energy Agency, Kyoto and KEK, Tsukuba, Japan

Received 24 November 2008 / Received in final form 18 February 2009

Abstract. The kind of laser extreme light infrastructure (ELI) provides will usher in a class of experiments we have only dreamed of for years. The characteristics that ELI brings in include: the highest intensity ever, large fluence, and relatively high repetition rate. A personal view of the author on the prospect of harnessing this unprecedented opportunity for advancing science of extreme fields is presented. The first characteristic of ELI, its intensity, will allow us to access, as many have stressed already, extreme fields that hover around the Schwinger field or at the very least the neighboring fields in which vacuum begins to behave as a nonlinear medium. In this sense, we are seriously probing the 'material' property of vacuum and thus the property that theory of relativity itself described and will entail. We will probe both special theory and general theory of relativity in regimes that have been never tested so far. We may see a glimpse into the reach of relativity or even its breakdown in some extreme regimes. We will learn Einstein and may even go beyond Einstein, if our journey is led. Laser-driven acceleration both by the laser field itself and by the wakefield that is triggered in a plasma is huge. Energies, if not luminosity, we can access, may be unprecedented going far beyond TeV. The nice thing about ELI is that it has relatively high repetition rate and average fluence as compared with other extreme lasers. This high fluence can be a key element that leads to applications to high energy physics, such as gamma-gamma collider driver experiment, and some gamma ray experiments that may be relevant in the frontier of photo-nuclear physics, and atomic energy applications. Needless to say, high fluence is one of most important features that industrial and medical applications may need. If we are lucky, we may see a door opens at the frontier of novel physics that may not be available by any other means. Finally, as the last lecture of this workshop the conference organizers charged this paper also to briefly reflect on the talks that have been given at the ELI meeting, which collectively pushed the envelope of the frontier of contemporary physics, an attempt is made to touch on as many talks as possible.

PACS. 52.27.Ny Relativistic plasmas

1 Introduction

The accelerator has been one of (if not the most) important scientific instruments of 20th century science. As known in the name of Livingtson's chart [1], we physicists have been able to exponentially increase its energy (and thus the resolution) ever since its inception. It is based on enormously sophisticated science and accompanied vast amount of technological prowess [2]. This has contributed to the truly revolutionary attainment of physical knowledge in the last century nearly over its entire period. However, this very tendency seems to have finally encountered a severe ceiling toward the end of the last century [3]. The current standard in accelerator physics is based on the rf (or radio-frequency) technology. It exploits the microwave technology that flourished since early 20th century.

Current high energy accelerators are based on the principle that electromagnetic waves of microwaves (rf or radio-frequency waves) excited in a metallic tube accelerate charged particles. In the metallic tube an alternating current (ac) flows, which drives these electromagnetic waves emanated away from the metal in vacuum. Based on this principle of acceleration, when we increase the intensity of electromagnetic waves, the penetrated electric field through the surface of the metal tends to knock out electrons in the metal into vacuum. The phenomenon is known as the breakdown (also as the sparking) phenomenon of the material by the electromagnetic waves. Typically metal breaks down much before the electric field reaches 100 MeV/m. If we consider electrons which are embedded in a binding potential on the order of eV in the material (typical of the solid state potential that binds the matter), we see it easy for electrons to be ripped away from this binding potential if they move more than the

---

[a] e-mail: `Toshiki.Tajima@physik.uni-muenchen.de`

inter-atomic distance of 10^{-1} nm. Such an electric field amounts to eV/0.1 nm = 100 MeV/cm. However, the real breakdown phenomenon is much more complex and it can be triggered by a mere single electron knocked out from the weakest bond of the lattice, which in turn triggers secondary electrons and so on causing a flood of ionization of electrons. This is an electric avalanche phenomenon. For example, an electron near a defect may suffer knockout from the bind with a much lower field. Thus in reality the sparking and breakdown begins much below the field intensity of 100 MeV/cm, in fact even much lower than 100 MeV/m. When we want to accelerate electrons to high energies (such as TeV), it tends to take multi-km. The fundamental reason for its large scale is based on this problem. To advance the knowledge of the smallest spatial scale, energies of the largest scale are desired. Thus we encounter an ever greater energy demand, and thus ever greater lengths of accelerators. Ordinarily, the cost of an (electron) accelerator is determined by the amount of necessary accelerating rf cavities and is proportional to its overall length. While this effort is quite important for mankind's attempt to reach for the highest energy frontier, it is understandable and laudable to hear a call for research for not an incremental improvement, but a rather revolutionary jump in increasing the accelerating gradient [4].

The present paper is a direct reflection of the author's talk at the workshop trying to touch on several selected topics that may serve to give the reader an impression of the kind of atmosphere that this field is brewing of late and therefore is not intended as a comprehensive review. Rather a perspective on extreme field science from one particular point of view throughout these varied topics is intended here, which may serve to look ahead and to overcome some of the difficulties we need to address by learning the past success and failure. Comprehensive reviews may be found for example in [5,6].

2 Laser acceleration and relativistic engineering

Laser acceleration [7] constitutes a radically new approach to accelerate particles to high energies. As was well known as the Lawson-Woodward Theorem [8], the transverse electromagnetic fields in free space cannot amount to a net acceleration. In a nut-shell this is because the transverse electric field of laser is ill fit for acceleration of particles in the longitudinal direction over a distance [9]. What is necessary is an intense electric field in the longitudinal direction that is (nearly) invariant over a sufficient time on the frame of the accelerated particle. The laser wakefield aforementioned [7] does just that and thus may be a possible answer to the challenge posed by Suzuki and Takasaki for a thousand-fold increase in accelerating gradients over the conventional rf acceleration. The contemporary intense laser technology is primarily owing to the chirped pulse amplification [10]. The wavelength of laser is several orders of magnitude shorter than that of rf. The available intensity of each may be even more disparately separate. This uniquely high intensity available from the laser technology is a part of the noteworthy ingredients of laser acceleration. What we should not overlook or underestimate is the corollary to this. That is, in order to achieve appropriate conditions for acceleration, the control and precision that we have to accomplish are far severer than in the case of rf. This is because the laser wavelength is several orders of magnitude shorter than rf and that much more demanding. Furthermore, the science and technology of rf-based accelerator has been enormously successful and sophisticated [1,2]. Laser acceleration needs to learn from such an asset of knowledge.

Once laser was invented in 1960, people quickly realized that the electric (or electromagnetic) fields of laser can be huge. In fact the present day high power laser can deliver electric fields of laser as great as 10^4 TeV/m [5]. Alas, as mentioned above, this electric field points to the wrong direction, that is, transverse to the direction of acceleration. There have been many proposals of laser acceleration [11]. Many proposals depend on 'tilting' the direction of laser so that the transverse field now offers a longitudinal component. However, it is easy to see that the phase velocity of light propagating obliquely to the direction of particles that be accelerated by the laser is greater than c. Thus, the laser wave phase will outrun eventually and ceases to accelerate particles. More detailed and mathematical way to state this difficulty is stated in the Lawson-Woodward Theorem [8]. In accelerator physics utilizing rf and metallic cavity this trouble is overcome by the introduction of the so-called 'slow wave structure'. A typical slow wave structure is a series of indented metallic structures periodically placed in the cavity so that the electromagnetic waves in the cavity slow down themselves. Thus the group velocity of the rf wave becomes less than c. Indented metallic structure is once again the prime position to start sparking upon applying high voltage rf. The phase velocity of laser has a similar problem, i.e. this is greater than the speed of light in a plasma, $v_{ph} = c/(1 - \omega_p^2/\omega^2)^{1/2}$, while the group velocity is $v_g = c^2/v_{ph}$.

In order to overcome this problem, one has to introduce a fundamentally new approach. An idea is to follow "Once you have eaten the poison, you might as well eat the dish" [12]. That is, if metal does break down under strong fields, we might as well use a material that is already broken down by strong fields and no longer break further. That is, plasma is embraced. Veksler first introduced the idea in which he used plasma as an accelerator medium in 1956 [13]. This is to excite "collective fields" in plasma by injecting an electron beam. The collective fields would be used to accelerate heavier ions, it was proposed. The name of collective fields arises from the notion to get accelerating electric fields that are excited by a large number of plasma electrons moving cooperatively. The supposed advantages were: (a) the cooperative electron motion collectively could give rise to a large amplitude of wave; (b) even when a huge wave is excited, the plasma no longer "breaks down", as it is already fully ionized. Unfortunately, in spite of many experiments that have been subsequently carried out, in these they encountered plasma instabilities and the accelerating fields turned into mess. (Such propensity to manifest instabilities and destruction of plasma structures is well known and documented in encyclopedic literature [14] and an infamous culprit for making a confined plasma becoming easily unstable.)

To circumvent this problem, the laser wakefield concept was introduced in which plasma waves resist the overtaking of the trailing part and eventual breaking of the wave because of the relativistic dynamics [7]. When the time scale of the laser pulse is as small as femtoseconds and the laser and wakefield pass by electrons and ions of the plasma, there is no time for sluggishly heavy ions to move. This leaves the plasma only regulated electron (so-called Langmuir) oscillations.

This enables us to create huge accelerating fields in matter, i.e. plasma, which can no longer be broken down, permitting to exceed well beyond the breakdown field ∼100 MeV/m that has stood an unwavering limit for break-down of metal (or other ordinary materials).

A collective force is one arising from cooperative phenomena, diagonally opposite to an individual force. The collective force becomes gigantic when a large number of particles move coherently in phase with the particular motion and the cooperative phenomenon arises. The collective force arising from a large number of N particles (where N is a macroscopically large number) may become gigantic, as compared with a force arising from a single particle. The plasma wakefield we mentioned, comprising from coherent electron motions, is a cooperative phenomenon and exhibits a large collective force. Our research has pointed to the fact that the plasma wakefield in a typical experimental conditions can well exceed 10 GeV/m. This electric field longitudinal to the direction of the propagation of the wave represents the intensity amounting from the essentially total polarization of plasma electrons over the wavelength of the Langmuir oscillations. The main reason why such an extreme electric field emerges is due to the situation where the amount of polarized charge attains the macroscopic level. However, when one embarks on a collective N particle system, these N particles have to be coherently organized to exert large collective force. Otherwise, chaos results. We need an organizational principle to maintain coherence of large number of particles from becoming chaotic.

For this purpose, what we call relativistic coherence may be introduced. It is the realization that enables us to combat against chaotic motion because particles approaching the speed of light (relativistic) cannot exceed c and thus they tend to acquire (nearly) the same velocity. The relativistic coherence may be compared with the oft-trodden quantum coherence, which manifests itself often when energies of matter become lower rather than higher. This relativistic coherence reinforces the reason why an immense field can be created without random or chaotic motions canceling each other. Typically, due to the nonlinearity of medium the higher the amplitude of the plasma wave is (when the amplitude becomes substantial), the farther it moves. In a case of plasma waves with non-relativistic phase velocity the wave breaks at the field that is equal to the amount at which the total polarization of plasma electrons mentioned above takes place. However, when the phase velocity is close to c, as the wavehead (the density peak) tries to overtake its preceding wavetrough (density depressions), more electrons gather toward the wavehead, but cannot spill over beyond this large peak. This effect further enhances the amplitude and sharpness of the wakefield peak. Because of this relativistic effect, the wakefield in the relativistic regime remains robust against wave breaking unlike in the non-relativistic regime, yielding the stability and coherency to relativistic wakefield. We may regard this resultant striking structure that well coheres in the relativistic regime as an example of “relativistic coherence”. In contrast to the well-known “quantum coherence” where the quantum mechanical mechanism is responsible for cohesion of matter, in our present case matter tends to cohere where relativistic effects provide mechanisms that lead to cohesion of matter. In relativistic regimes the speed with which matter moves converges toward c. Matter bunches up shrinking in its width, typically by a factor of $1/\gamma$, where γ is the Lorentz factor of matter. Radiation emitted off relativistic matter is focused more narrowly with its radiative angle shrinking by a factor of $1/\gamma$. On the other hand, the oncoming electromagnetic field encountered by speeding matter is enhanced by a factor of γ. Laser acceleration using plasma as accelerating medium fully utilizes these effects [7]. The electron energy that the laser wakefield can accelerate to is thus given in the one-dimensional wakefield structure case as

$$\varepsilon_e = a_0^2\, mc^2\, \gamma_{ph}^2 = a_0^2\, mc^2\, (n_c/n_e), \tag{1}$$

where γ_{ph} is the Lorentz factor of the plasma phase velocity, a_0 is the normalized vector potential of the laser electric field appearing here due to the relativistic quivering motion of electrons in the intense laser field, n_c is the critical density of the plasma at the laser frequency, and n_e the electron density. The typically large factor of (n_c/n_e) arises due to the relativistic speed of the wake, and a_0^2 arises due to the enhanced stability of the wake from breaking (and heavier relativistic mass of electrons that constitute the wake) in the relativistic regime of laser. Note that in this expression the electron energy scales proportional to the laser intensity I. It has been pointed out, however, that formula (1) is subject to modification in cases where 2 and 3 dimensional geometries matter [5]. Further, when the intensity of laser exceeds 10^{23} W/cm^2, the radiative friction on electrons become not ignorable and electron dynamics deviates from the classical picture [15]. At further higher intensity ($>10^{24}$ W/cm^2) the quantum mechanical effects become important [16]. Care is thus needed to apply equation (1) to extreme high intensities that may be expected in ELI experiments. Nonetheless, it is intriguing to see that if one gets $n_e = 10^{16}$/cc and $I = 10^{22}$ W/cm^2, equation (1) yields energies of 10^9 MeV, or PeV, when the one-dimensional formula is justified [17,18]. It would take a laser with energy of

10's MJ and subpicosecond pulse length. At ELI parameters a test of scaling principles toward such extreme energies scaled down to 10 TeV with 10's kJ and 10's fs may be possible. It should be noted that the observation of cosmic rays of electrons and/or γ's tend to become rapidly miniscule beyond TeV. This is because they interact with matters and other fields (such as magnetic fields) too strongly as energy increases in this regime. Thus the creation of electrons and thus γ's beyond TeV by itself nicely complements cosmic ray observation. Before exploration of these ephemeral high energy events, now there began a consideration of laser acceleration as an option for future collider research [19].

It is perhaps possible to launch a systematic scientific paradigm or technological platform that consciously takes advantage of these effects to realize frontier physics and parameter regimes that are otherwise hard to reach [20]. Such an intellectual endeavor may be called "relativistic engineering" [21]. There is now emergence of vigorous research of relativistic engineering developing in addition to the laser wakefield. This includes relativistic flying mirrors [20] using wakefield, relativistic mirror using the surface of a sold [22], relativistic mirror using a thin foil [23], relativistic whistler [24], relativistic ion sheet [25], relativistic decelerator [26], laser wakefield bunch-slicer and buncher, and many more. Many talks at the ELI workshop were dedicated to this subject and its applications were quite startling [27–30].

In addition to these relativistic engineering applications also presented were ideas to provide compact future X-ray light sources [31–34]. Relativistic dynamics of electrons on the surface of a solid can also give rise to coherent generation of higher harmonics [35].

3 Laser acceleration of ions

The earliest introduction of collective acceleration was by Veksler, as mentioned in Section 2. In this he proposed the use of plasma into which an electron beam is injected to cause large amplitude electric fields of collective nature. His motivation at that time must have been based on the fact that while electrons fly nearly at speed of light, the ion velocity is far below it. Thus if the electric field was properly excited by the electron beam, ions can follow electrons, or more precisely the waves that are excited by electron beam. Since ion mass M is far greater than that of electrons m, if ions acquire the same velocity as that of electrons, the energy would multiply by a factor of M/m in the nonrelativistic limit. Many a year later a rendition similar to this in a fresher fashion was reintroduced by Chen et al. [36]. In their work, a driver, laser pulse, that was introduced by Tajima and Dawson to excite the wakefield was now replaced by a bunch of electron beam. Thus wakefield in Chen et al. is now produced by a bunched electron beam. A first experiment using the electron-bunch driven wakefield was carried out by Nakajima et al. [37]. A similar effect of collective plasma force may be employed to stop high energy charged particles over a short distance without causing a large amount of radiation in matter, if we adopt the wakefield excited by the entering beam bunch and to be decelerated by this large field [26], another example of collective force in action. Such a collective decelerator can be compact and facilitate to reduce a large amount of possibly damaging radiation, and even allow to convert a portion of the high and intense beam energy directly into electricity. As the intensity level goes up in the laser lab and the derivative radiation level becomes of concern, the importance of such a devise to take care of the downstream side of science and applications experiments may dramatically increase. Such an effort of taking care of the downstream side of science and technology impact that manifests itself more emphatically in the 21st century may be called as part of 'toilet science' as opposed to 'kitchen science' of the upstream [38].

As mentioned earlier, in 1970's there have been exploratory experiments to drive collective electric fields by electron beams [39,40]. In a typical of these experimental setups, one would find that electron beam is injected into a gas or plasma separated by a metallic wall of the chamber [41]. In an attempt to better understand recent laser driven acceleration of ions let us try to study some details of this experiment and its theoretical understanding. In this experiment a relativistic electron beam transits through a metallic wall and enters into plasma. These experiments began to reveal several characteristics of the acceleration mechanism. The entrant electron beam causes space charge separation between the electron bunch and the metallic wall, forming a sheath. As more and more electrons enter, the electrostatic potential rises, which decelerate the bulk of electrons. Thus the overall electron bunch begins reflexing, or oscillations. While the bunch decelerates, it is hoped that ions present get accelerated forward. In Mako et al. work it was found that ion acceleration proceeds only up to a certain point, beyond which most of decelerated electrons overshoot the accelerated ions, ceasing the accelerating phase. Thus the achieved ion energy is not scaling to $(M/m)\varepsilon_e$, but stops short at mere several times ε_e. A similar is found in the recent laser ion acceleration experiments.

In order to explain this experimentally found phenomenon, Mako and Tajima [42] provided a theoretical and simulational model. To review this rather old work helps serve how to overcome some of the challenges that laser ion acceleration faces today, that is, the abrupt termination of the sheath that was formed by the laser irradiation and the rather slow rise of ion energy as a function of laser intensity. Their model adopted the fully nonlinear nonrelativistic ion dynamics by a set of moment equations (the fluid equations) self-consistently coupled with the Poisson equation and Vlasov electrons (unlike thermal electrons such as Mora's model [43] developed specifically laser heated electrons). The set of these coupled nonlinear equations have been solved exactly, seeking for self-similar evolution solutions. The resultant solution is a closed form that takes algebraic expression in a simple case. The derived ion energy spectrum shows a power law dependence that tapers off toward high energies and cuts off abruptly at the highest energy. This is a characteristic behavior of sheath acceleration. This generic tendency has been observed in their own simulation as well as their experiment and elsewhere.

The ion spectrum that Mako and Tajima found interesting properties. First, it exhibits a power-law energy dependence. Second, it shows an energy cutoff. It cuts off on the order of the electron beam energy. The arising sheath breakup and the subsequent backward over-shooting of electrons are the culprit of this termination of ion energy spectrum in their experimental case. Third, this cutoff energy, or in another word the maximum energy that ions can attain, according to [42], is several times the energy of the electron beam. This factor corroborates well with the factor of 'several' often observed in many experiments. Fourth, most importantly, this method works for cases in which laser interaction with thin target or cluster target where thermal electrons are not expected. This work indicates, therefore, that unless one can institute a much smoother process of electron beam entry into the plasma and thus smoother ion acceleration, the ongoing abrupt sheath acceleration approach stops short of desired more energetic acceleration.

In 2000 when the team of scientists [44] carried out the irradiation of large energy Petawatt laser on a metallic foil. From the backside of the foil, it was observed, the acceleration of energetic ions up to 60 MeV emerged in the case of Snavely et al. Their interpretation was that the laser pulse on the metal produced highly relativistic electrons (perhaps more energetic in the forward direction than any other directions) up to 10's MeV, penetrating through the metallic foil. Once high energy electrons come out of the foil surface and ionized hydrogen ions get accelerated by the sheath formed by these energetic electrons. We find that this situation is similar to the Mako et al.'s experimental one. Snavely et al.'s experiment and others [38] should have a broad energy spectrum of electrons, as they were created by the laser irradiation that heats up electrons with a broad energy spectrum. Besides this difference, the commonality is that the resultant ion acceleration ceases to continue after the sheath electrons are reflected back (resulting in sheath breakup) by the huge electrostatic field due to change separation between electrons and ions. Thus we expect that the ion acceleration energy by such laser irradiation of solid foil (either metal or otherwise, which quickly becomes a plasma, showing a similar sheath dynamics) is limited by (several times) the electron energy. Since most of accelerated electron energy in this mechanism is arising from the laser heating of electrons (by its strong transverse quivering motion under laser electromagnetic fields), the electron energy typically scales as $\sqrt{I}$, where I is the intensity of the laser. This square-root dependence is unlike the laser wakefield acceleration, equation (1).

Since Snavely et al.'s epoch making experiment, a large number of experiments on laser driven ion acceleration have been carried out [44]. In these experiments (since there are large variations in experimental conditions, data also vary widely), the ion energy, broadly speaking, distributes in fact scaling as $\sqrt{I}$. Moreover, it is our observation that the ion energy is limited by (only several times) the electron energy:

$$\varepsilon_i \sim (\text{several})\ \varepsilon_e \propto \sqrt{I}. \tag{2}$$

4 How to avoid the sheath breakup

It thus follows that in order to overcome this limitation of ion acceleration, it is essential to avoid the sheath collapse and electron backward overshooting. What one can suggest is to have a gentler and gradual electron cloud entry in the ion acceleration process. This is in contrast to the above abrupt and non-adiabatic fashion of ion acceleration. In order to make the acceleration gradual and adiabatic, Rau and Tajima [45] suggested the need to control the phase velocity of the accelerating structure in such a way to reduce it to near zero first, and there gradually accelerate it to higher values. For this purpose Rau et al. produced an example of using an Alfven shock where the propagation of the accelerating structure (of magnetized shock) may be controlled either by the plasma density or magnetic field. An alternative is to use a target whose electron density is not far above the critical density as is the case for an appropriately ablated solid target [46]. In Yogo et al.'s experiment [47] the plasma density was reduced from the solid density to not far above the critical density by the prepulse ablation. As a more controlled method of pursuing a medium that can sustain slow pickup of ions, another example, a cluster target, was proposed [48]. Such targets upon laser irradiation should be capable of making the laser pulse screech to a near halt of the photon pulse propagation at the point of ion pickup, then letting the laser pulse entering in a less dense and faster propagation phase for a graded spatial control of the acceleration process. If such non-sudden and gradual (i.e. adiabatic) acceleration can be realized, there is no reason that ion acceleration is limited to (several times) the electron energy. (If this happens, the scaling of $I^{1/2}$ need not manifest. Under such a circumstance, we expect that the ion energy gain is once again proportional to the mass ratio times that of electron energy, which in turn may scale as I instead of $I^{1/2}$, just as in the case of laser wakefield acceleration.) This expectation arises from the orderly adiabatic acceleration of ions held in a wave-like structure (the structure acting as if a 'basket' holding an 'egg'), as opposed to the terminating sudden acceleration by sheath created by a solid target.

Laser wakefield acceleration was one of methods to capture electrons in an orderly wave ('basket') and coherently accelerate electrons. Even though electrons are much lighter than ions and thus it is much more tolerant against rapid acceleration, over the years we have already learned [49] that if electron acceleration happens smoothly from the bulk electrons to trapped electrons via a smooth crossing of the separatrix, the electron energy spectrum should show a much sharper monoenergy feature. This is the reason why the laser wakefield acceleration experiments [50] in 2004 found more pronounced monoenergetic electron spectra than in earlier experiments.

The same should apply to ion acceleration, albeit the adiabatic time scale for ion acceleration should be much longer than that of electron pickup. Fukuda et al. [51] have devised a target with large clusters with diameter on the order of photon wavelength, which permitted high energy ion acceleration with even very modest power laser irradiation. This is because the cluster target allows the laser EM fields to slow down and reaccelerate with ions trapped on the wave. In understanding the experiment by Fukuda et al. [51] it may be ventured that clusters whose above-critical density towers over the non-evanescent gaseous regions slow down or pin the progression of the laser pulse, while gaseous regions unoccupied by clusters allow the propagation of the laser phase front unimpeded. This dynamics would give rise to a sling-shot like structure of laser front and result in pent-up electromagnetic stress of the laser fields, which may directly accelerate some of the ions in the cluster (this is in addition to the electrostatic fields that are generated by the blown-out electrons out of the cluster un-restored back). When the laser electromagnetic fields are impeded in progress and their stress mounts at the cluster pinning points, one would expect, this means that the frontal portion of the laser pulse retards while the backside keeps arriving, giving rise to a compression of the pulse and thus an overall blue-shift of the laser spectrum. The sling-shot mechanism discussed here and Fukuda et al. must have observed in [51] may provide a possibility of accelerating ions to energies much more than, and of forming tightly bunched ions from the cluster much tighter than, those expected from the sheath acceleration.

Finally, we note that when ions (protons) become relativistic in the field of laser at around $I = 10^{24}$ W/cm^2, protons begin to behave relativistically and they are like electrons around the intensity of $I = 10^{18}$ W/cm^2. Thus protons may be picked up and accelerated with ease as it were for electrons driven effectively by the radiation pressure [25] and in this case the energy of ions once again scales similarly to the case of laser wakefield acceleration, proportional to I. In this case ions quickly follow electrons and the laser pulse so that sometime the regime is called the radiative acceleration regime of ions. Thence ion acceleration may show monoenergetic spectrum, unlike the sheath acceleration. ELI should be able to test this idea. In fact once protons (or other species of ions) are accelerated relativistically, they may be injected into wakefields so that they can surf on them to even greater energies. This provides a new possibility to have a compact (even) high(er) energy ion accelerator driven by laser.

In extending or following this idea, it would be possible to adopt the radiative pressure and accompanying electrostatic fields for accelerating ions from a robust and thin solid surface with a very clean (i.e. with little preceding pedestal of the pulse energy) pulse even at intensities below the aforementioned intensity [23]. Earlier, Esirkepov et al. and others [46,52] arrived at the optimized acceleration condition of ions driven by a short pulse laser irradiation on a target (at high densities) over a broad range of the laser intensity. This condition states:

$$\sigma = a_0, \tag{3}$$

where σ is the areal density of the target (normalized) as $\int n/n_{cr} dl/\lambda$, and a_0 is the normalized vector potential of the laser. It is found in [52] that the accelerated ion energy now scales linearly proportional to the intensity I, if the target design is subject to the constraint of (3). The condition (3) may be rewritten into a relation between the optimal laser field E and the optimal target thickness l_t with density n as

$$E^2/4\pi = n\mathcal{E}_B(nr_B^3)(l_t/r_B)^2/\pi, \tag{4}$$

where r_B is the Bohr radius and $\mathcal{E}_B = e^2/r_B$ is twice the Rydberg energy. In a solid or liquid the factor (nr_B^3) amounts to a ballpark on the order of unity. Thus for a solid target with the thickness on the order of (10's) nm a laser intensity would be near optimal approximately on the order of 10^{20} W/cm^2 (with latitude, depending on how one takes into account an appropriate density of ionized electrons). If we consider the above mentioned liquid cluster target (its diameter in [51] was $\sim 1\,\mu$), it would be likely that the cluster electron density at the time of sling-shot acceleration may become less than the original liquid density (say, likely down to near critical), which would correspond to an approximately optimal intensity of laser on the order of 10^{19} W/cm^2 according to equation (4). As mentioned above, in both cases it is anticipated blue-shift of the transmitted laser spectrum due to the laser front compression at the target. In this ELI Workshop Hegelich [53] has shown a remarkable high energy ion acceleration experiment by irradiating a very thin (10 s of nm or less) diamond-like carbon with intense laser. In this case a thinly prepared carbon (with the diamond carbon bond being robust) foil, irradiated with an exceptionally high contrast laser pulse with sufficiently high intensity, withstands its breakdown prior to the main pulse arrival and allows its relatively small mass in the thin target to be directly accelerated by the energetic photon pulse. It may be speculated that their parameters are in a close neighborhood of equation (4). In this case, the sheath breakup is mitigated via a path of holding electrons and ions together under the large impinging photon pressure from behind, alternative to the gradual and adiabatic method of ion acceleration mentioned earlier [45–48,51,54]. It may not be without merit to mention that currently analysis of some of these experiments is under way and it is already evident that electron collective motions under the intense fields are reasonably preserved through the ultrathin foil and thus the dynamics of electrons is anything but thermal. Such a condition helps to increase ion energies beyond the thermally driven sheath. In fact when electrons preserve collective motions, the model [42] remains applicable and shows predictive capability. Once such sheath breakup avoidance becomes possible, ions are easier to get accelerated to high energies. Then again the more energetic ions become, the easier they get accelerated because ions begin to move in more synchronous with the driving pulse. When relativistic ions come into play, many new applications open up (e.g. [55]). Related works were also presented at this workshop [47,56–61].

5 Schwinger field physics

The kind of power and intensity that ELI may be able to accomplish brings us to unprecedented studies of high field science [5]. An optimistic intended intensity of 10^{26} W/cm^2 is still far from the Schwinger field intensity in the neighborhood of 10^{29} W/cm^2. However, even before the vacuum breakdown at the Schwinger field, there should appear many phenomena related to the deviation of the linear vacuum response of the Maxwell's equation and manifestations of nonlinear quantum electrodynamics (QED) [62]. These include: multi-photon processes in vacuum such as the Breit-Wheeler process, vacuum birefringence, higher harmonic generation in vacuum, vacuum nonlinear dielectric effects such as self-focusing, etc. This may be understood as a parallel similarity to the nonlinear optical effects that arise in dielectric media under sufficient intensity of laser (such as 10^{11} W/cm^2) where the intense electric fields polarize the atomic electrons that are bound to their atomic nucleus and when the displacement of these electrons become sufficiently large from the equilibrium orbit the restoring force tends to deviate from the harmonic one. This is the origin of various nonlinearities of media under strong laser fields and now studied well under nonlinear optics [63]. In this workshop there have been a large number of papers touching on this nonlinear QED phenomenon exploration with ultraintense laser fields.

If we are lucky, the probing of vacuum under intense field may lead to even more dramatic development. Unlike the research carried out by particle collisions by such experiments like collider, the intense laser provides a probe macroscopic (on the order of a micron range as compared with a spatial extent much less than fm) property of vacuum nonlinear behavior. This may lead to revelation of unexpected and unexplored cooperative phenomena of vacuum. Since one explores the low energy end of the field as compared with collider physics, one may be able to sift some physics that may be buried by noise in experiments in the high energy end such as in collider. These may include the exploration of low energy particle physics such as presumed but never found low mass particles like axions [64]. Some of the low energy 'stuff' might include candidates for dark matter and even dark energy, whatever they may be.

Here, instead of delving into details, let us simply refer to many talks given on these subjects at the workshop [65–84]. For example, Dunne [68] reviewed the current theoretical status of computations of the vacuum pair production process, first modern language of renormalized quantum field theory by Schwinger in 1951. Experimentally, this is a new, totally unexplored non-perturbative regime of quantum electrodynamics, to which ELI should provide access for the first time. It is straightforward to estimate the exponential factor in the probability for such nonperturbative vacuum particle production, and this leads to the critical electric field of 10^{16} V/cm. However, this estimate is for a constant and uniform field, and the fields in the ELI laser are spatially focused and temporally pulsed. The big challenge theoretically is to find reliable computations of the vacuum pair production rate for a realistic background electromagnetic field that accurately models the physical ELI laser field. Recent analyses by Narozhnyi et al. [82] and by Schuetzhold et al. [83] have shown that by appropriately shaping of the electromagnetic pulses one can achieve significant enhancement of the vacuum pair production effect, bringing it closer to the reach of the ELI project. At present, the only formalism that has obtained results for more general electromagnetic field configurations is the worldline instanton approach to the QED effective action. An even more interesting theoretical question, soon to be of practical experimental importance, is: what happens when the effective electric field exceeds the Schwinger critical field?

Here it is suggested that some combination of intense laser with additional scientific instruments such as (either conventional or laser-driven) accelerator, one can access even more nonlinear regimes of QED or even reach or exceed the Schwinger field. An electron that is accelerated to high energy with Lorentz factor of γ sees relativistically contracted electromagnetic fields of the laser if the electron beam and laser are counterinjected. The wavelength and the pulse length are seen shortened by the factor γ. Thus the observed electromagnetic fields on the frame of the electron is enhanced by a factor γ^2. With a modest γ of 10^3 the electron would feel the equivalent intensity well beyond the Schwinger intensity. A challenge is placed on the theorists at the ELI workshop to investigate the effects of this in the QED and beyond under this circumstance. This is a good example of the marriage of laser and accelerator that can push the frontier of science that otherwise (either single laser or accelerator alone) may not be explored. It is noteworthy here that the capacity of the facility of ELI (or such equivalent facility) may be unique in providing high energy accelerated electron beam and laser simultaneously in a synchronous way, because the laser can drive high energy electron beam so that both electron beam and laser are naturally synchronized. It is our belief that such marriage of laser and accelerator will further enrich fundamental science and applications much further along in the future [21]. There may be more ways to make such marriage than a simple combination of counterstreaming laser and electron beam. For example, by employing relativistic engineering mentioned above, we may be combining laser and a relativistic mirror to create high intensity gamma rays that are monochromatic, directed, high fluence, and ultrafast. Gamma rays thus produced are not only of high energy ($4\gamma^2\omega$, where ω is the laser frequency), but also is ultrashort compress by a factor $1/\gamma^2$. Thus this stands as part of a reply to the call by Suzuki and Takasaki [4]. Such gamma ray sources would bring out novel investigations of photo-nuclear physics [84,85].

6 Physics under immense acceleration

Another important aspect of extreme high field science arises from the immense acceleration that this kind of field wields on an electron. According to the Equivalence Principle of Einstein, such an enormous acceleration amounts to an enormous gravitation. The acceleration a is up to the order 10^{30} cm/s^2. Because of such intense acceleration, one can conduct experiments that explore the validity of the Equivalence Principle deep in the extreme acceleration regime. Some of the tests of Equivalence Principle have been in a very modest acceleration using neutrons (Ref. [79]). Not only that, it may help test some of the implications of the theory of relativity. The huge acceleration can make the distance to the horizon for the accelerated electron become quite short $d = c^2/a$, where d is the distance to the horizon. This shrinkage of horizon from infinity to finite can bring a host of interesting experiments one can conduct. A class of experiments may be to explore the field theory in curved geometry, including the Unruh radiation [87]. Because of the Equivalence Principle, it is believed that (other than some minor details) the Unruh radiation is equivalent to Hawking radiation [88]. It is thus of importance to explore this with vigor. This will help us understand the implication of Hawking radiation. Many authors in fact presented their investigations on this aspect at this workshop (e.g. [65,66,68,69,77,78]). Based on Chen and Tajima [89] and later Schuetzwald [69], there may be a window of opportunity to observe such radiation over the noise of Larmor radiation. We leave detailed discussions to other papers in this volume. However, it is worthy to note that a much more systematic theoretical investigation has been launched and a meaningful interdisciplinary discussion between the high field science and field theoretic physics commenced [65]. In his presentation, he reverberated the theme of high field science as the one 'exploring some issues of fundamental physics that have eluded man's probe so far'. In that he listed the quantum field theory exploration that may be carried out by 'high amplitude' rather than the conventional 'high energy momentum' approach. He further went on to list discovery potential of several possible areas:

(a) ALP's (axion-like particles): hypothetical Nambu-Goldstone bosons such as axions, majorons, familons, etc.;
(b) mini-charged particles;
(c) paraphotons; and
(d) submillimeter forces.

The exploration of dark energy in laboratory is not easy, and it appears particularly the case by high momemntum approach. The 'high amplitude' approach may provide a unique tool for this endeavor. It is noted also that recent reports (PAMELA [90]; Chang et al. [91]) of high energy (100 GeV–TeV) γ's and electrons in space seem to yield a signal of positrons (and electrons) excess anomaly. This might turn out to be a signature of long-sought after dark matter. It is tempting to speculate a possibility that ELI may be able to provide extreme high energy γ rays with given energies from laser accelerated electrons provides a window of opportunity to back up such cosmic observations in laboratories. (Also pointed out by earlier authors with high energy γ's are the exploration of checks of special theory of relativity in extreme Lorentz factor [92–94]. However, the current astrophysical observations of far away gamma ray bursts seem to indicate the deviation if any is not large enough to be identified and thus laboratory observation of any effects is still remote.)

7 Conclusion

In conclusion today, we face an unprecedented prospect for a new class of extreme field science, with which we foresee a transforming technique of laser acceleration that, meeting the challenge of Suzuki and Takasaki's call for 'thousand-fold increase' movement [4], can radically compactify the size of and broaden the scope of accelerator applications, shorten the pulse of energy of coherent X-rays reaching attoseconds and even zeptoseconds regime. The former can make not only table top modest energy (such as GeV) accelerators, but may give a future basis for energy frontier accelerators such as linear colliders. Not only the collective acceleration provides the future laboratory accelerator method, but it may provide an answer to puzzles in astronomical phenomena of high energy cosmic rays and gamma rays events. For example, cosmic rays (presumably protons beyond energies of 10^{19} eV) may not be generated by the venerable Fermi stochastic acceleration mechanism, as that would lose more energy than gain one by emitting copious synchrotron radiation from even protons at the stochastic 'pinball scatterings' of Fermi. Compact and prompt collective acceleration with strong fields that nature provides may be needed to resolve the puzzle, a mechanism not unlike the one we have discussed here. Such as the one discussed in [95] may be an example for compact acceleration mechanism that nature offers. This way astrophysical compact acceleration attains extreme high energies without losing their energies to synchrotron radiation. More over some of the recent observations of high energy gamma ray astronomy present many puzzles, such as copious gamma ray emission from AGN (active galactic nuclei) with vary small time scales [96]. Here the small time scale means that the accelerating agent's compactness and thus intense way of acceleration. Non-collective acceleration mechanisms seem to fall short and to be too feeble to account for such phenomena, which once again may lead to a case to be accounted for with the collective field acceleration mentioned here. Several speakers touched on topics related to astrophysical relevance such as [27,97–103].

The extreme fields that the new generation of laser promises to deliver can open novel ways to conduct investigations of fundamental physics beyond the method through collisions of high energy charged particles. A gamma-gamma collider utilizing electron accelerators may be considered as one of the steps of such. This topic was discussed by several people including Serbo [104], Habs [105], Baur [106], Mueller [107]. It is possible, it seems, that a gamma-gamma collider may make a collider construct more affordable. One of the reasons for this is the greater signal-to-noise ratio for new discoveries with gamma-gamma collisions than with charged particles.

On the other hand, unlike a collider physics in which events are confined to point-like spacetime, extreme fields of laser may allow to study macroscopic (micron scale) property of vacuum, the texture of vacuum and its property in curved spacetime. This may be regarded as an extension of particle-field physics to macroscales or as to materials science of particle-fields physics of vacuum. We may initiate what may be called 'Schwinger field physics', which certainly includes nonlinear QED, but perhaps we may also stumble into new physics such as 'low mass' high energy physics. We may be able to severely examine the extent and validity of special and general theory of relativity in extreme energies as well as in extreme acceleration/gravitation. For example, is the Equivalence Principle valid in such a regime?

We emphasize the opportunity of employing not just the high fields of laser, but also accelerator driven particle beams in combination with high fields, a marriage of laser and accelerator, so to speak. By cleverly exploiting the consequences of relativity, which may be called 'relativistic engineering', we may be able to enhance either the laser field further (such as intensity, pulse length compression, the photon energy multiplication). Many examples have been discussed in the workshop, spurting growing research interest in this direction as well. With such a technique one may be access extreme fields such as the Schwinger fields, or the power threshold of vacuum laser self-focusing [5]. By colliding laser and high energy the effective field felt by the electron in the oncoming beam may be enhanced and thus allow us to access much higher fields, as already partially exploited in the pioneering experiment at SLAC [108]. The kind of parameters ELI can provide pushes the physics far into the fully non-perturbative QED regime. The laser Compton gamma rays that are created by intense laser backscattered by the counterstreaming high energy electron beam provides not only high energy gamma rays (including for the purpose of the aforementioned gamma-gamma collider application), but also brilliance ever increasing higher with higher energy [109]. Such gamma rays are ideal tools for probing nuclei. In the past most nuclear physics investigations have been conducted via collision events of charged particles. This is somewhat akin to the situation in atomic physics before the invention of laser, when most of atomic physics techniques were based on atomic collisions. With the introduction of laser, extremely precise laser spectroscopy has exploded, but also many new techniques of laser probe and control of atoms have commenced. A parallel may be brought about with the availability of directed energy-specific, brilliant gamma beams in nuclear physics. We may call this as photo-nuclear physics, which may as well revitalize nuclear physics (see a paper in this issue by Habs et al. [84]).

We need to acknowledge that in order to accomplish these lofty goals, we need to confront formidable challenges that are accompanied by this new way of doing science in the miniature spatial scales and ultrafast time scales as compared with the conventional rf technology. These challenges demand equally unprecedented accuracy and sensitive control of lasers, interacting media, and optics, as well as uncharted physical parameter domains we encounter. New ways to measure and feedback for the purpose of control need to be invented and instituted in these new endeavors. It takes a great deal of creativity and experience to master the task in hand. We need to share the best knowledge and results to maximize the progress from all who are engaged. It is also quite important to inherit the large body of the crown jewel of accelerator physics that has been accumulated and systematized in the past, and to extend the knowledge into the new regime. If these can be garnered, immediate applications to industrial usages as well as eventual utilization to medical purposes may be also within a scope.

I would like to acknowledge informative, encouraging, and collegial discussions by Drs. S. Bulanov, G. Mourou, T. Esirkepov, K. Nakajima, Y. Kato, M. Downer, C. Siders, K. Yokoya, A. Chao, P.S. Chen, L.M. Chen, H. Daido, A. Yogo, M. Tampo, M. Kando, H. Kotaki, Y. Fukuda, A. Faenov, A. Pirozhkov, H. Kiriyama, D. Habs, F. Krausz, M. Fujiwara, C. Barty, R. Hajima, F. Takasaki, A. Suzuki, K. Fujii, N. Toge, Y. Kamiya, P. Bolton, J. Mizuki, S. Kawanishi, K. Kondo, T. Takahashi, K. Homma, R. Kodama, A. Sugiyama, G. Korn, M. Hegelich, C. Barnes, S. Steinke, X.Q. Yan, J. Rafelski, H. Gies, G. Dunne, A. Caldwell, and M. Teshima. From so many others I have benefited and learned and I apologize for any oversight of those whom I fail to mention here. I further wish to comment that since the present paper is a result of my ELI Workshop presentation and reflects its flavor, rough edges, and short deadline to prepare, it is not intended to thoroughly cover a large field of scientific literature of enormous values. I apologize any lack of mentioning of those important works. The purpose of the present paper remains an attempt to simply alert the enormous and unique potential opportunity that ELI presents from the author's point of view.

This work was supported in part by the Special Coordination Fund (SCF) for Promoting Science and Technology commissioned by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan and in part by the DFG Cluster of Excellence MAP (Munich-Centre for Advanced Photonics) and the European Commission under contract ELI pp. 212105 in the framework of the program FP7 Infrastructures-2007-1.

References

1. M. Livingstone, J. Blewett, *Particle Accelerators* (McGraw-Hill, NY, 1962)
2. *Handbook of Accelerator Physics and Engineering*, edited by A. Chao, M. Tigner (World Scientific, Singapore, 1999)
3. *The Future of Accelerator Physics*, edited by T. Tajima (AIP, NY, 1996)
4. A. Suzuki, F. Takasaki, private communication (2007); A. Suzuki, Outlook: Accelerator Science, in *ICFA Workshop* (SLAC, Stanford, 2008)

5. G.A. Mourou, T. Tajima, S.V. Bulanov, Rev. Mod. Phys. **78**, 309 (2006)
6. M. Marklund, P. Shukla, Rev. Mod. Phys. **78**, 591 (2006)
7. T. Tajima, J. Dawson, Phys. Rev. Lett. **43**, 267 (1979)
8. J. Lawson, *The Physics of Charged Particle Beams* (Clarendon, Oxford, 1977)
9. T. Tajima, Laser Part. Beams **3**, 351 (1985)
10. D. Strickland, G.A. Mourou, Opt. Commun. **56**, 219 (1985)
11. *Laser Acceleration of Particles*, edited by P.J. Channel (AIP, NY, 1982)
12. T. Tajima, in *First International Symposium on Laser-Driven Relativistic Plasmas Applied to Science, Industry and Medicine*, AIP Conference Proceedings, edited by S.V. Bulanov, H. Daido (AIP, NY, 2008), p. 52 *The statement in* [12] *(l.9 from bottom, p. 53) should read that "the group velocity", rather than "the phase velocity as well as group velocity".*
13. V.I. Veksler, in *CERN Symposium on High Energy Accelerators and Pion Physics* (CERN, Genova, 1956), p. 80
14. A. Mikhailovskii, *Theory of Plasma Instabilities* (Consultant Bureau, NY, 1974)
15. A. Zhidkov, J. Koga, A. Sasaki, M. Uesaka, Phys. Rev. Lett. **88**, 185009 (2002)
16. S.V. Bulanov, T. Esirkepov, J.K. Koga, T. Tajima, D. Farina, Plasma Phys. Rep. **30**, 196 (2004)
17. M. Kando et al., in *First International Symposium on Laser-Driven Relativistic Plasmas Applied to Science, Industry and Medicine*, AIP Conference Proceedings, edited by S.V. Bulanov and H. Daido (AIP, NY, 2008), p. 19
18. J. Koga, in *Applications in Laser-Plasma Interactions*, edited by S. Eliezer, K. Mima (CRC, Roca Baton, 2009)
19. T. Raubenheimer, Advanced Accelerator Concepts Workshop (2008)
20. S. Bulanov, T. Esirkepov, T. Tajima, Phys. Rev. Lett. **91**, 085001 (2003)
21. T. Tajima, in *Proc. Japan-Hungary Seminar*, edited by J. Kanamori (IIAS, Kyoto, 2002)
22. N. Naumova et al., Phys. Rev. Lett. **92**, 063902 (2004)
23. O. Klimo, J. Psikal, J. Limpouch, Phys. Rev. ST Accel. Beams **11**, 031301 (2008)
24. S.V. Bulanov et al., Phys. Rev. E **67**, 016405 (2003)
25. T. Esirkepov, M. Borghesi, S. Bulanov, G. Mourou, T. Tajima, Phys. Rev. Lett. **92**, 175003 (2004)
26. M. Kando et al., in *First International Symposium on Laser-Driven Relativistic Plasmas Applied to Science, Industry and Medicine*, AIP Conference Proceedings, edited by S.V. Bulanov, H. Daido (AIP, NY, 2008), p. 197
27. S. Bulanov, presented at the ELI Workshop (2008)
28. J. Meyer-Ter-Vehn, presented at the ELI Workshop (2008)
29. T. Esirkepov, presented at the ELI Workshop (2008)
30. M. Kando, presented at the ELI Workshop (2008)
31. D. Habs, presented at the ELI Workshop (2008)
32. A. Pukhov, presented at the ELI Workshop (2008)
33. R. Hoerlein, presented at the ELI Workshop (2008)
34. H. Ruhl, presented at the ELI Workshop (2008)
35. U. Teubner et al., Phys. Rev. Lett. **92**, 185001 (2004)
36. P. Chen et al., Phys. Rev. Lett. **54**, 693 (1985)
37. K. Nakajima et al., Nucl. Instrum. Meth. A **292**, 12 (1990); later by SLC/UCLA groups
38. T. Tajima, `http://wwwapr.kansai.jaea.go.jp/presen/presen.html` (2006)
39. N. Rostoker, M. Reiser, *Collective Methods of Acceleration* (Harwood Academic, London, 1978); M. Reiser, *Theory and Design of Changed Particle Beams* (Wiley, NY, 1994)
40. S. Humphrey, *Charged Particle Beams* (Wiley, NY, 1990)
41. T. Tajima, F. Mako, Phys. Fluids **21**, 1459 (1978)
42. F. Mako, T. Tajima, Phys. Fluids **27**, 1815 (1984)
43. P. Mora, Phys. Rev. Lett. **90**, 185002 (2003)
44. E. Clarke et al., Phys. Rev. Lett. **84**, 670 (2000); A. Maksimchuk et al., Phys. Rev. Lett. **84**, 4108 (2000); R.A. Snavely et al., Phys. Rev. Lett. **85**, 2945 (2000). A review of many of recent works may be found in: J. Fuchs et al., Nature Phys. **2**, 48 (2006)
45. B. Rau, T. Tajima, Phys. Plasmas **5**, 3575 (1998)
46. K. Matsukado et al., Phys. Rev. Lett. **91**, 215001 (2003)
47. A. Yogo, presented at the ELI Workshop (2008); A. Yogo et al., Phys. Rev. E **77**, 016401 (2007)
48. T. Tajima, US Patent 6867419B2 and US patent 6906338B2 (2005)
49. S. Bulanov, T. Tajima, J. Part. Accel. Soc. Jpn **2**, 35 (2005); T. Esirkepov, S.V. Bulanov, M. Yamagiwa, T. Tajima, Phys. Rev. Lett. **96**, 014803 (2006)
50. S. Mangles et al., Nature **431**, 535 (2004); C. Geddes et al., Nature **431**, 538 (2004); J. Faures et al., Nature **431**, 541 (2004)
51. Y. Fukuda, A.Ya. Faenov, M. Tampo, A. Yogo, M. Kando, Y. Hayashi, T. Kameshima, A. Pirozhkov, T. Esirkepov, T. Nakamura, K. Ogura, M. Mori, H. Sakaki, T.A. Pikuz, A.S. Boldarev, V.A. Gasilov, P. Bolton, R. Kodama, T. Tajima, H. Daido, S.V. Bulanov, *High energy ion acceleration by repetitive laser irradiation of cluster-gas target*, presented at APS (2008)
52. T. Esirkepov, M. Yamagiwa, T. Tajima, Phys. Rev. Lett. **96**, 105001 (2006); X.Q. Yan et al., Phys. Rev. Lett. **100**, 135003 (2008); S. Rykovanov et al., New J. Phys. **10**, 113005 (2008)
53. M. Hegelich, presented at the ELI Workshop (2008)
54. M. Murakami et al., in *First International Symposium on Laser-Driven Relativistic Plasmas Applied to Science, Industry and Medicine*, AIP Conference Proceedings, edited by S.V. Bulanov and H. Daido (AIP, NY, 2008), p. 275
55. F. Terranova et al., Nucl. Phys., Sect. B Proc. Suppl. **143**, 572 (2005)
56. O. Klimo, presented at the ELI Workshop (2008)
57. A. Henig, presented at the ELI Workshop (2008)
58. T. Liseykina, presented at the ELI Workshop (2008)
59. F. Pegoraro, presented at the ELI Workshop (2008)
60. M. Chen, presented at the ELI Workshop (2008)
61. J. Schreiber, presented at the ELI Workshop (2008)
62. For example, W. Dittrich, H. Gies, *Probing the Quantum Vacuum: Perturbative Effective Action Approach in Quantum Electrodynamics and Its Applications* (Springer, Berlin, 2000)
63. N. Bloembergen, *Nonlinear Optics* (Addison-Wesley, Reading, MA, 1965)
64. K. Homma, *Presentation at International Workshop on Physics and Technology of Laser-Electron Interaction toward the ILC* (2007)
65. H. Gies, J. Phys. A **41**, 164039 (2008); H. Gies, presented at the ELI Workshop (2008)
66. M. Marklund, presented at the ELI Workshop (2008)

67. A. Dipiazza, presented at the ELI Workshop (2008)
68. G. Dunne, presented at the ELI Workshop (2008)
69. R. Schuetzwald, presented at the ELI Workshop (2008)
70. T. Heinzl, presented at the ELI Workshop (2008)
71. H. Reiss, presented at the ELI Workshop (2008)
72. M. Dekieviert, presented at the ELI Workshop (2008)
73. J. Rafelski, presented at the ELI Workshop (2008)
74. A. Zayakin, presented at the ELI Workshop (2008)
75. A. Smilga, presented at the ELI Workshop (2008)
76. T. Cohen, presented at the ELI Workshop (2008)
77. P. Thirolf, presented at the ELI Workshop (2008)
78. H. Weirfurter, presented at the ELI Workshop (2008)
79. L. Labun, presented at the ELI Workshop (2008)
80. F. Heberstreit, presented at the ELI Workshop (2008)
81. D. Blanschke, presented at the ELI Workshop (2008)
82. N.B. Narozhny et al., Phys. Lett. A **330**, 1 (2004)
83. R. Schuetzhold, H. Gies, G.V. Dunne, Phys. Rev. Lett. **101**, 130404 (2008)
84. D. Habs, T. Tajima, J. Schreiber, C.P.J. Barty, M. Fujiwara, P.G. Thirolf, Eur. Phys. J. D (2009) `DOI: 10.1140/epjd/e2009-00101-2`
85. G. Priebe et al., presented at the ELI Workshop (2008)
86. R. Colella et al., Phys. Rev. Lett. **34**, 1472 (1975); U. Bonne et al., Phys. Rev. Lett. **51**, 1401 (1983)
87. W. Unruh, Phys. Rev. D **14**, 870 (1976)
88. S.W. Hawking, Nature **248**, 30 (1974)
89. P.S. Chen, T. Tajima, Phys. Rev. Lett. **83**, 256 (1999)
90. O. Adriani et al. (PAMELA collaboration), `arXiv:0810.4995` (2008)
91. J. Chang et al., Nature **456**, 362 (2008)
92. H. Sato, T. Tati, Prog. Theor. Phys. **47**, 1788 (1972)
93. S. Coleman, S. Glashow, Phys. Lett. B **405**, 249 (1997)
94. G. Amelino-Camelia et al., Nature **393**, 763 (1998)
95. P.S. Chen, T. Tajima, Y. Takahashi, Phys. Rev. Lett. **89**, 161101 (2002)
96. M. Teshima, private communication (2008); M. Hayashida, Ph.D. thesis (LMU, Munich, 2008)
97. R. Diehl, presented at the ELI Workshop (2008)
98. V.S. Beskin, presented at the ELI Workshop (2008)
99. A. Kim, presented at the ELI Workshop (2008)
100. N.M. Naumova, presented at the ELI Workshop (2008)
101. N. Kumar, presented at the ELI Workshop (2008)
102. M. Thoma, presented at the ELI Workshop (2008)
103. I. Kuznetsova, presented at the ELI Workshop (2008)
104. M. Serbo, presented at the ELI Workshop (2008)
105. D. Habs, presented at the ELI Workshop (2008)
106. G. Baur, presented at the ELI Workshop (2008)
107. C. Mueller, presented at the ELI Workshop (2008)
108. C.K. Bula et al., Phys. Rev. Lett. **76**, 3116 (1996); D.L. Burke et al., Phys. Rev. Lett. **79**, 1626 (1997)
109. W. Bertozzi et al., Phys. Rev. C **78**, 041601 (2008); N. Kikuzawa et al., APEX **2**, 03652 (2009); C. Barty, T. Tajima, private communication (2008)