IZEST Vision: Laser-driven Fundamental Particle Physics Paradigm

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(1) Scope of Highest Intensity Lasers

The laser aspires to be the next possible paradigm in Fundamental / Particle Physics. By its coherence, monochromaticity and field magnitude, it has been the lynchpin of novel spectroscopic methods of investigation that deepened our understanding of the atomic structure. However, it was inefficient to probe the subsequent strata formed by the nucleus, the nucleon or the vacuum. Neither the laser photon energy nor its electric field have been large enough to conceive decisive experiments beyond the atomic level.

To reach the level where relevant nuclear and/or high energy physics investigations could be undertaken, large-scale laser infrastructures capable to deliver intensity in the ultra relativistic regime have been recently conceived based on the original concept introduced in 2002 (Tajima and Mourou)

The first embodiment is ELI. It was launched under the aegis of the European Union community and built in Czech Republic, Hungary and Romania. It will yield the highest peak power and laser focused intensity. With its peak power of 100 PW, it represents the largest planned civilian laser project in the world. This gargantuan power will be obtained by delivering few kJ in 10 fs. Focusing this power over a micrometer spot size will yield intensities in the 10^{25} W/cm^2 range, well into the ultrarelativistic regime. This extremely high peak intensity will correspond to the highest electric field, but also according to the pulse intensity-duration conjecture (Mourou and Tajima 2011) to the shortest pulse of high-energy particles and radiations, in the attosecond-zeptosecond regime.

(2) Going beyond ELI is IZEST

With ELI, the particle energy, radiation and field produced would reach the entry point for relevant Nuclear Physics, High Energy Physics or Vacuum Physics with our high intensity lasers.

The second initiative is promulgated by the International center on Zetta-Exawatt Science and Technology (IZEST) which was opened last year. It endeavors at the generation of exawatt-zettawat pulses produced by the delivery of greater than 10kJ in less than 10fs. It relies on already built large scale fusion lasers like the LMJ or NIF. To get around the grating damage threshold conundrum, a novel compression technique known as C^3 (Cascaded Compression Conversion) was conceived (Mourou et al., 2012). It relies on the astute combination of the three compression techniques, CPA, OPCPA and Backward Raman Amplification(BRA). Based on plasma, C^3 exhibits a much superior damage threshold ($10^{3\text{-}4}$) than CPA or OPCPA alone. It could potentially compress greater than 100kJ to the femtosecond regime paving the way to the exawatt-zettawatt regime and laser based particle physics.

(3) Going to TeV Laser Accelerator with kJ Lasers

When we try to reach for 100GeV and beyond (such as TeV) whose energies are sufficiently high for the frontier of high energy physics such as the search and study of Higgs boson, it is advantageous to employ kJ lasers (Nakajima et al. 2011). We realize that in order to reduce the required overall electric power needed to drive the accelerator, the average power of electricity to drive is proportional to the square root of the plasma density. This scaling also tells us that the laser energy per stage that is required to drive the laser accelerator is inversely proportional to the density to the power of 3/2. This means that in order to reduce the average power needed by 10 the cost of the accelerator by 10, we need to decrease the plasma density by 100, while we need to increase the individual laser energy by 1000. This is therefore preferred route towards the eventual high energy laser accelerator. It may be called the low density paradigm of laser acceleration. In addition to the above main advantage, it has a large number of superior performances as accelerator, such as less betatron radiation and consequentially reduced beam degradation, less stages and its therefore reduced beam degradation, smaller emittance degradation due to the jitters, etc. On the other hand, the expected elongation of the acceleration length is minor (as the optical connection between the stages are substantial and contributes to longer machine for higher densities) and in fact does not reflect in cost, as the cost is not much in creating gas tubes.

In order to test and promote this paradigm, we need a 1-10kJ laser. IZEST equipped with the PETAL laser is ideally suited to first test this concept in this parameter regime. We plan to test toward 100GeV class experiments with or without staging. With sufficient amount of laser energy at PETAL and LMU, we regard that its extension can be TeV.

(4) IZEST and the Nonluminosity Paradigm

We would like to point out that there are a class of fundamental physics questions that may be explored without having high luminosity. We suggest that the employment of MJ laser such as LMJ could reach TeV and even PeV (Tajima et al., 2011). Reaching this level of energies with even a small number of electrons has a significance, as we can test the validity of special theory of relativity by measuring the speed of light as a function of energy of the gamma photon in extreme high energies. This has been tried utilizing the arrivals of gamma photons (up to GeV) from Gamma Ray Bursts (GRBs), highest brightness of astrophysical objects thus farthest (Ellis; Abdo et al.). Even though there appears to be some systematic delay of arrivals in higher end of gamma rays from GRBs, it is not clear if the delay is coming from the violation of Eintein's theory or due to the mechanism of accelerating high-energy particles in GRBs. Our laboratory acceleration can make a definitive test in par with the farthest edge GRB arrival, if we can make a precision measurement as we proposed.

It is also possible to observe the synchrotron radiation spectrum from TeV and PeV electrons in these experiments. Synchrotron radiation is from the betatron oscillations of such high energy electrons in laser acceleration(Ostermayr et al. 2012). It has been considered by B. Altschul (2008) about the deviation of the well-known spectrum if there is a certain violation of Einstein's theory.

There are a broader class of questions, however, in the extreme High Energy Cosmic Ray community (Ebisuzaki, et al. 2012) that if there are highest energy cosmic rays in the range of 10^21eV. If so what are the objects that emit such and what are the mechanism for such. It is already clear to us that cosmic rays beyond 10^19eV that have been observed (up to 20^20eV) cannot be created by the well-know Fermi's acceleration. This is because the Fermi's acceleration assumes stochastic acceleration. When proton energy exceeds 10^19eV, the kick of protons in random directions would lose most of their energies into synchrotron radiations, even for protons. Thus it is incumbent for us to come up with a mechanism of extreme high energy acceleration. It may be possible to suggest that wakefield acceleration can provide a very compact prompt linear acceleration to extreme high energies that are required for this purpose (Takahashi et al. 2000; Chen et al. 2002).

In addition, we envision that the zeptosecond streaking we are considering using the colliding lasers and copropagating gamma photon can make time domain measurement of the vacuum (Tajima and Homma, 2012). As particle pairs emerge from vacuum, we could test its mass dependence as a function of time. Such may be expected on quark pairs, as they are assumed to be clothed by gluons very heavily and their masses are dependent on how these gluon clothes are. In the naked vacuum state are quark mass much lighter than meson mass? This has been measured in high-energy collision events. Can we see this when they emerge from vacuum? Does its mass increases as it gets out of vacuum into a real particles? How? The proposed zeptosecond measurement may be able to answer this question. Furthermore, we might even see mass evolution of more mundane electrons and positrons.

(5) High-average Power Lasers. IZEST Introduction to a Novel Laser Architecture (ICAN EU Project)

The low-density paradigm is beneficial for reducing the overall average power. However, we still need on the order of 10-100MW of electric power for lasers from the wallplug. In order to keep this number reasonable, it is also tantamount to have high efficiency of such drive lasers.

The ICAN (International Coherent Amplification Network) is a EU project (see the HP) addressing the question of high average power and high efficiency laser technology that is required for the driver of the laser accelerator based collider. ICAN has identified the fiber laser technology as the prime candidate for this driver. It has made significant technological leap so that we can begin to see the eventual outcome of this technology product now. Figure 1 show an artist view of such a laser. The concept relies on the coherent phasing of a large multiplicity of Yb-doped fibers. The possibility to replace a single amplifying bulk material by a large number of fibers (greater than 10^4) increases enormously the cooling surface area. Fiber can also be pumped efficiently by laser diodes and offers a way towards superior laser wall plug to efficiency i.e >30%. Each fiber provides a single mode. Phased together they provide a way to reach single large pulse energy with great control. The noise analysis of single mode fiber shows that the main source of noise is thermal and at low frequencies (10Hz) making easy to control each fiber with electrooptic components. Experiments have demonstrated the phasing of 64 fiber in CW(J. Bourderionnet et al. 2011) and make possible to envision the massive coherent phasing of 10^4 fibers à 10kHz. Nonlinear effects was also shown that they could be mitigated. Assuming 1mJ per fiber, CAN systems have the potential to deliver 10J/pulse, sub picosecond @10kHz or an average of 100kW with an efficiency surpassing 30% or 1000times what is demonstrated today. By combining a number of modules together the MW average could be easily been reached. Thus ICAN could be a fulcrum element of future laser-driven high energy accelerator. Let's note the project ICAN benefit from the invaluable experience of astronomers involved in the construction of the 42 m ESO telescope in Chilie. The telescope is composed of 1000 mirrors and 40000actuators activated a frequency of 2000 Hz. From the correction view point ICAN and the ETL are very close.

(6) Vacuum Search by Intense Fields

By employing copious coherent photons coming out from kJ-MJ lasers, we envision that the excitation of fields that have not manifested so far may become within our reach. The weakly coming dark particles escaped our detection so far, such as Dark Matter and Dark Energy, except for the astrophysical inferences. It remains a big mystery as of the property of these entities for now and laboratory experiments are badly needed. Homma et al. (2011; 2012) have introduced the degenerate four wave mixing technique to the possible detection of very weakly coupling fields by intense lasers. By virtue of the resonance of co-parallel laser pulses, we can enhance the gain by some 70 orders of magnitude if we apply kJ-MJ lasers over the charged particle collisions. Therefore, even weakly coupling Dark Matter candidates such as Axion-like Particles may be within the detectability and even more elusive Dark Energy candidates. Some candidates of these particles are believed to be very light. Therefore, it is best to employ light particles, in our case massless light itself, albeit with a huge quantity in coherence.

(7) IZEST exploring the possibility to produce Zettawatt (10^{21}W)Pulse

As we mentioned in 2002, we introduced a possibility that we could achieve coherent fields at ZW level using highest energy lasers available in the world. With the IZEST launch in 2011, this theoretical possibility is coming into a more real project possibility, as PETAL and LMJ commit themselves toward fundamental research applications of kJ-MJ lasers. MJ systems are comprised of around 200beams of 10-20kJ beams. In order to realize coherent laser power at ZW, we need to have a technology that allow to compress and cohere a multiplicity of laser pulses into a single giant ultrashort pulse with peak power and intensity1000 times what is planned with ELI. Towards this goal the C^3 * concept (Mourou et al. 2012) was introduced, as mentioned earlier. When this level of large energy, ultrahigh intense laser pulses are generated, we are in the stage to explore not only the above laser acceleration in highest energy frontiers, but also in the nonlinear field search of vacuum, including QE vacuum and beyond. Also as mentioned, because of the intensity-pulse duration conjecture (Mourou and Tajima, 2011), this means the fastest possible optics. This will allow us to explore realtime view of physics in subatomic world, rather than the conventional energy spectrum views. For example, in the conventional technique we see the steady state, while in the time-domain approach utilizing ultrafast optics, we shall be able to see in principle such a phenomenon as the quarks (or electrons) coming out of vacuum first as bare elementary particles and later gradually wearing clothes to become real particles in a dynamical process.

*C3 Stands for Cascaded Conversion Compression

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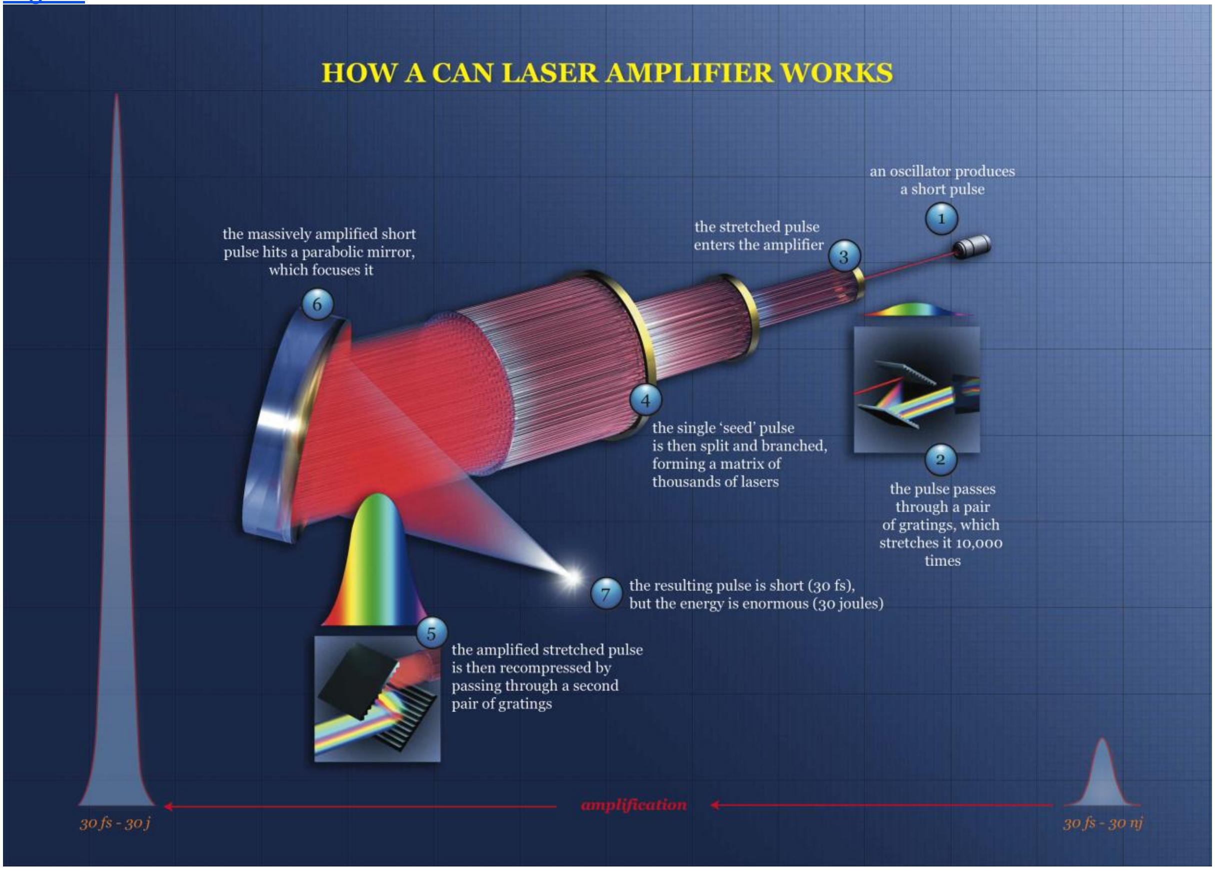
Fig. 1:



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This figure illustrates the difference between the amplifying structure in a conventional CPA system. In A the amplifier is made of a bulk material. In B the amplification sytem is based on the concept CAN where the amplifying material is composed of a large multiplicity of Yb: doped single mode fibers phased together. In both cases the amplifying material is he same. In B, the large surface area will allow the generation of much superior average power generation.