Ultra High Intensity Lasers:
The Pulse Intensity-Duration Conjecture

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Abstract

In this paper we show quantitatively that the pulse duration and intensity of lasers (or derived coherent radiation bursts) are linearly related over more than 18 orders of magnitude, from millisecond to zeptosecond (see Fig.1). It leads to the surprising conclusion that the shortest energy radiation/particle bursts are to be produced by the highest power laser, which is to say the most energetic and largest sized laser. This result leads to the counter-intuitive conclusion that the shortest coherent pulse should come from a largest sized laser like ELI, NIF, or the Laser Megajoule. In addition, these short pulses will be necessarily in the X-ray and γ-ray regimes, opening a route to time resolved nuclear, vacuum nonlinearities and nonlinear QED physics exploration.

A few years ago a new type of large scale laser infrastructure specifically conceived to produce the highest peak power and focused intensity was announced by the European Community: the Extreme Light Infrastructure, ELI[1], designed to be the first exawatt class laser yielding 1000 times the power of NIF. This gargantuan power will be obtained by producing a kJ of energy over a mere 10fs.

The motivation underpinning the push toward this extreme power[2] was not only ultrahigh laser intensity and the associated field that could be attained. Also significant is the prospect to produce exceedingly short bursts of energetic radiation and particles. This is rooted in what we call the Pulse Intensity-Duration Conjecture. Based on quantitative observations, this states: "*To decrease the ACHIEVABLE pulse duration, we must first increase the intensity." It is the exact converse of the all too obvious declaration that "to increase the ACHIEVABLE peak intensity for a given energy, we must shorten the pulse duration."*

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Checking the Laser Pulse Intensity-Duration Conjecture

The first laser demonstrated by T. Maiman in 1960[3] was working in the **free-running** mode with peak powers in the kW and internal intensity in the kW/cm^2 with an overall pulse duration in the microsecond regime. In 1961, the **Q-switching** concept was demonstrated[4] moving the internal peak intensity to the MW/cm^2 dictated by the Q-switch dye saturation intensity. The pulse duration is in the nanosecond range. In 1965, the **Mode-Locking**[5] operation in ruby, based on dye molecules as saturable absorbers, was observed. Due to the dye's fast transparency recovery of the order of 1ps the dye attains a much higher saturation intensity. It results in laser peak intensities in the GW/cm^2 range and pulse durations in the single picosecond regime. Switching from solid state amplifying materials – Ruby, Nd: Glass, Nd: YAG – to dye amplifying materials combined with the technique of Colliding Pulse Mode-Locking (CPM), pulses from 100fs [6] to 27fs [7] duration were demonstrated.

Moving away from dye resonance as the mode-locking mechanism to the use of the intensity dependent index of refraction ($n=n_0 +n_2I$) of the amplifier medium itself led to the demonstration of a simple and robust method (**KLM Mode-Locking**)[8] in conjunction with the very large gain-bandwidth of Ti:sapphire. Being out of resonance demands a heftier driving intensity of the order of 1TW/cm^2. The pulse produced could be close to 10fs or shorter[9-11]. At this point the pulse bandwidth is challenging the largest amplifying bandwidth material: Ti:sapphire.

To go shorter, the pulse needs to acquire a broader spectrum before it can be recompressed. This is accomplished in a gas-filled-hollow fiber[12]. The pulse bandwidth is broadened by self-phase-modulation and stretched by group velocity dispersion. The pulse is recompressed by dispersive elements like chirped mirrors to 4.5fs[13] or two light periods. Throughout this operation the pulse intensity is kept below 10^{14}W/cm^2, the gas ionization threshold, in order not to lose the bound electrons in atoms/molecules. An alternative approach based on molecular phase modulation in gases has led to a pulse duration in the 3.8fs with 10^{12}W/cm^2 intensiy[14].

At this point we have reached the single cycle limit of 2.6fs for 800nm, the Ti:Sapphire's wavelength. To go shorter than one light period, we need to generate new frequencies. This is done by **High Harmonic Generation**[15] in a gas jet. The laser intensity is increased by focusing the compressed pulse beam after the fiber and the compressor in a gas jet. The laser harmonics are created up to a cut-off frequency $\hbar\omega_c = U_p + 3.17 I_p$ [16], where U_p is the ponderomotive potential energy and I_p the ionization potential. A fraction of the harmonic spectrum is selected to produce down to 100as[17,18] pulses, the shortest being at 80as[19].

If we want to go even shorter, we need to resort to even higher intensities and leave the nonlinear bound electron regime to go into the **relativistic** regime which is for 1μm wavelength greater than 10^{18}W/cm^2. This type of intensity is today commonly available using Chirped Pulse Amplification[20] and also Optical Parametric Chirped Pulse Amplification[21] systems.

In the relativistic regime, electrons oscillating in the laser field become relativistic and change their "mass" during their oscillations by a factor proportional to the Lorentz factor γ, which in turn is also proportional to the normalized vector potential a_0. If a laser pulse can produce this intensity at the target surface, the enormous ponderomotive laser pressure makes the electron critical surface oscillate in and out at relativistic velocity. As a consequence, the light impinged on this oscillating mirror is modulated periodically, resulting in high harmonics[22,23]. **Relativistic High Harmonic Generation** gives the prospect of a much broader harmonic spectrum, higher efficiency with no cut-off defined by the plasma frequency[22,24]. This has been experimentally verified[25] using the long pulse duration (300fs) of the Vulcan laser and observing the 3200th harmonic order.

A related scheme was shown based on a few cycle pulse, focused on one λ^2 –this is the so called λ^3-regime[26] - the relativistic mirror ceases to be planar and deforms due to the indentation created by the focused gaussian beam. As it moves, PIC simulation shows, it simultaneously compresses the pulses but also broadcasts them in specific directions. This technique provides an elegant possibility to both compress but also isolate individual attosecond pulses. The predicted pulse duration scales like T=600(*attosecond*)/a_0. Here a_0 is again the normalized vector potential, which is about unity at 10^{18}W/cm^2 and scales as the square root of the intensity. For intensity of the order of 10^{22}W/cm^2 the compressed pulse could be of the order of only a few attoseconds. The same authors have simulated the generation of thin sheets of electrons with γ of few tens with attosecond duration[27]. They could provide a way to produce by coherent Thomson scattering efficient beams of X-rays or even γ-rays. A similar concept called 'relativistic flying mirror' has been advocated and demonstrated[28], using a thin sheet of accelerated electrons. Reflection from this relativistic mirror leads to a high efficiency and pulse compression.

When one wishes to go beyond coherent X-rays to gamma rays, the 'mirror' that compresses the laser into gamma rays has to be of extremely high density (~ 10^{27}cm^{-3}) so that the laser may be coherently reflected into gamma photons. We suggest here that this may be achieved by a combination of the relativistically flying mirror just mentioned above with the implosion of this flying mirror so that its density may be enhanced by ten times in each dimension (thus thousand-fold in its density). We surmise that this may be achieved by a large energy pulse (~MJ) at the ultra-relativistic (even ions become relativistically moving in the optical fields) intensity of 10^{24}W/cm^2 on a partial shell of a concave spherical target. This imploding ultra-relativistic flying mirror[29] is capable of coherently backscattering an injected 10keV coherent X-ray pulse mentioned above[26], producing a possibility of coherent gamma rays of 100ys duration.

We have learned that: matter exhibits nonlinearities when strong enough laser is irradiated; manifested nonlinearities vary depending on the strength of the 'bending' field (and thus the intensity). The stronger we 'bend' the constituent matter, the more rigid the 'bending' force we need to exert; the more rigid the force is, the higher the restoring frequency (or the shorter the time scale) is. The nonlinearities of matter may vary, but this response is universal, ranging over molecular, atomic, plasma electronic and ionic, and even the stiffest of all vacuum, nonlinearities. Thus we have witnessed a sweep of nature's display of the universal behavior of direct correlation between the pulse shortness and the intensity of its driving laser over the widest intensity range our laboratory has to ever offer.

In conclusion, evidences over more than 18 orders of magnitude of the Pulse Intensity-Duration Conjecture have been accumulated experimentally and with simulation. It shows that the pulse duration goes inversely with the intensity from the millisecond to the attosecond and zeptosecond, using values from experiments and simulation. Most notably it predicts that the shortest coherent pulse in the zeptosecond-yoctosecond regime should be produced by the largest laser, like ELI or NIF and the Megajoule, if they are reconfigurated[30] in femtosecond pulse systems.

This Conjecture may provide an invaluable guide for future ultra intense and short pulse experiments. It fosters the hope that zeptosecond and perhaps yocto second pulses could be produced using kJ-MJ systems. It opens up the possibility to take snap shots of nuclear reactions and to peek into the nuclear interior in the same way that Zewail[31] examined chemical reactions or Corkum and Krausz[32] probed atoms. The other exciting prospect is the possibility to study the nonlinear optical properties of vacuum. This Conjecture ties the three distinct disciplines of science, i.e. ultrafast science, high field science, and large-energy laser science together with a single stroke.

References:

1. www.extreme-light-infrastructure.eu

2. G. A. Mourou, T. Tajima, S. V. Bulanov, Optics in the relativistic regime. *Rev. Mod. Phys.* **78**, 309-371 (2006).

3. T. H. Maiman, Stimulated Optical Radiation in Ruby. *Nature* **187**, 493-494 (1960).

4. R. W. Hellwarth, *Advances in Quantum Electronics* (Columbia University Press, New York, 1961).

5. H. W. Mokers, R. J. Collins, *Mode competition and self-locking effects in a Q-switched ruby laser. Appl. Phys. Lett.* **7**, 270 (1965).

6. R. L. Fork, I. Green, C. V. Shank, Generation of optical pulses shorter than 0.1 psec by colliding pulse mode locking. *Appl. Phys. Lett*. **38**, 671-672 (1981).

7. J. A. Valdmanis, R. L. Fork, J. P. Gordon, Generation of optical pulses as short as 27 femtoseconds directly from a laser balancing self-phase modulation, group-velocity dispersion, saturable absorption, and saturable gain. *Opt. Lett.* **10**, 131-133 (1985).

8. D. E. Spence, P. N. Kean, W. Sibbett, 60-fsec pulse generation from a self-mode-locked Ti:sapphire laser. *Opt. Lett.* **16,** 42-44 (1991).

9. A. Stingl, M. Lenzner, Ch. Spielmann, F. Krausz, R. Szipocs, Sub-10fs mirror-controlled Ti: Sapphire laser*. Opt. Let.,* **20***,* 602 (1995).

10. D. H. Sutter *et al*., Sub-6-fs pulses from a SESAM-assisted Kerr-lens modelocked Ti:sapphire laser: at the frontiers of ultrashort pulse generation. *Appl. Phys. B* **70**, S5-S12 (2000).

11. R. Ell *et al*., Generation of 5-fs pulses and octave-spanning spectra. *Opt. Lett.* **26**, 373-375 (2001).

12. M. Nisoli, S. De Silvestri, O. Svelto, Generation of high energy 10 fs pulses by a new pulse compression technique. *Appl. Phys. Lett*. **68**, 2793-2795 (1996).

13. M. Nisoli *et al*., Compression of high-energy laser pulses below 5fs. *Opt. Lett.* **22**, 522-524 (1997).

14. N. Zhavoronkov, G. Korn, Generation of single intense short optical pulses by ultrafast molecular phase modulation. *Phys. Rev. Lett.* **88**, 203901 (2002).

15. P. Antoine, A. L'Huillier, M. Lewenstein, Attosecond pulse trains using high–order harmonics. *Phys. Rev. Lett*. **77**, 1234–1237 (1996).

16. P. Corkum, Plasma perspective on strong field multiphoton ionization. *Phys. Rev. Lett.* **71**, 1994-1997 (1993).

17. M. Hentschel *et al*., Attosecond metrology. *Nature* **414**, 509–513 (2001).

18. M. Lucchini *et al*., Generation of high-energy isolated attosecond pulses. Paper presented at the *31st ECLIM*, Budapest, Hungary, 6-10 September 2010.

19. E. Goulielmakis *et al*., Attosecond control and measurement: lightwave electronics. *Science* **320**, 1614 (2008).

20. D. Strickland, G. Mourou, Compression of amplified chirped optical pulses. *Opt. Commun*. **56**, 219-221 (1985).

21. A. Dubietis *et al.,* Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal. *Opt. Commun*. **88**, 433 (1992).

22. S. V. Bulanov, N. M. Naumova, F. Pegoraro, Interaction of an ultrashort, relativistically strong laser pulse with an overdense plasma. *Phys. Plasmas* **1**, 745-575 (1994).

23. G. D. Tsakiris, K. Eidmann, J. Meyer-ter-Vehn, F. Krausz, Route to intense single attosecond pulses. *New J. Phys.* **8**, 19 (2006).

24. T. Baeva, S. Gordienko, A. Pukhov, Theory of high-order harmonic generation in relativistic laser interaction with overdense plasma. *Phys. Rev. E* **74**, 046404 (2006).

25. B. Dromey *et al*., *Nat. Phys*. **2**, 456 (2006).

26. N. M. Naumova, J. A. Nees, I. V. Sokolov, B. Hou, G. Mourou, Relativistic generation of isolated attosecond pulses in a λ^3 focal volume. *Phys. Rev. Lett*. **92**, 063902 (2004).

27. N. Naumova *et al*., Attosecond electron bunches. *Phys. Rev. Lett.* **93**, 195003 (2004).

28. S. V. Bulanov, T. Esirkepov, T. Tajima, Light intensification towards the Schwinger limit. *Phys. Rev. Lett.* **91**, 085001 (2003).

29. T. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, T. Tajima, Highly efficient relativistic-ion generation in the laser piston regime. *Phys. Rev. Lett.* **92**, 175003 (2004).

30. T. Tajima, G. A. Mourou, Zettawatt-exawatt lasers and their applications in ultrastrong-field physics, *Phys. Rev. STAB* **5**, 031301 (2002).

31. A. Zewail, Femtochemistry: atomic-scale dynamics of the chemical bond. *J. Phys. Chem. A* **104**, 5660–5694 (2000).

32. P. B. Corkum, F. Krausz, Attosecond science. *Nat. Phys.* **3,** 381-387 (2007).

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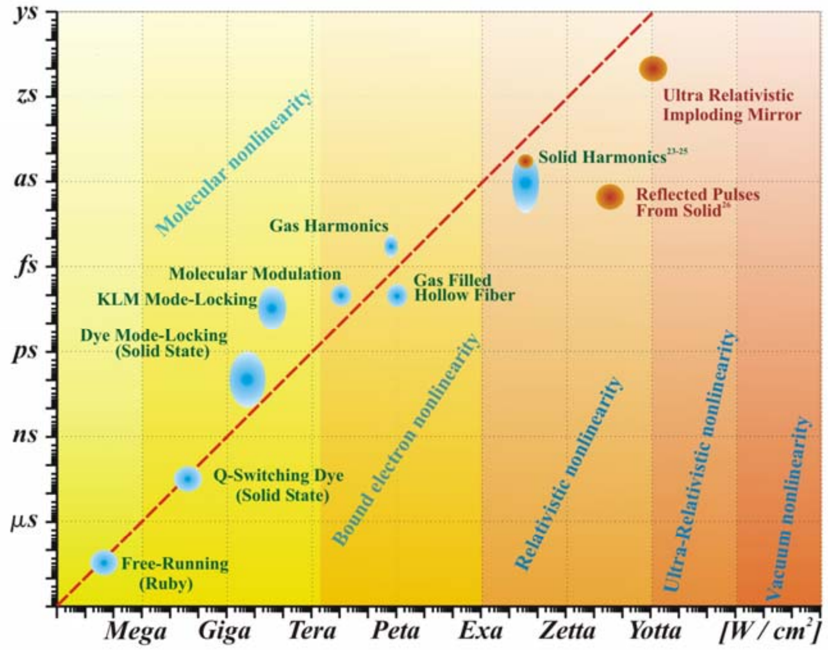

Fig.1: The Pulse Intensity-Duration Conjecture is shown. An inverse linear dependence exists between the pulse duration of coherent light emission and its intensity of the laser driver in the generation volume over 18 orders of magnitude. These entries encompass different underlying physical regimes, whose nonlinearities are arising from molecular, bound atomic electron, relativistic plasma, and ultra-relativistic, and further eventually from vacuum nature. The blue patches are from the experiments, while the red from the simulation or theory.