HIGH-INTENSITY LASERS IN NUCLEAR SCIENCE

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Summary

Recent developments in high intensity lasers open up a new approach to investigating nuclear reactions in the laboratory without access to nuclear reactors or particle accelerators. By focusing the laser spot, very high laser intensities in excess of 10^{21} W cm^{-2} can now be produced. Under these conditions, matter in the focal spot is turned into hot dense relativistic plasma. The laser interactions with solid or gas targets can generate collimated beams of highly energetic electrons and ions. The possibility of accelerating electrons to energies over 200 MeV in such experiments led to the utilization of high-energy bremsstrahlung radiation in order to investigate laser-induced gamma reactions. Laser-induced activation, transmutation, fission and fusion have been demonstrated with both single pulse giant laser systems and laboratory tabletop laser systems.

1. Introduction

Recent advances in laser technology now make it possible to induce nuclear reactions with light beams. When focused to an area of a few tens of square micrometers, the laser radiation can reach intensities greater than 10^{20} W cm^{-2}. By focusing such a laser onto a target, the beam generates plasma with temperatures of ten billion degrees (10^{10} K) – temperatures comparable to those that occurred one second after the "big bang".

With the help of modern compact high-intensity lasers (Figure 1), it is now possible to produce highly relativistic plasma in which nuclear reactions such as fusion, photo-nuclear reactions, and fission of nuclei have been demonstrated to occur. This new development opens the path to a variety of highly interesting applications, the realization of which requires continued investigation of fundamental processes by both theory and experiment and in parallel the study of selected applications. The possibility of accelerating electrons in focused laser fields was first discussed by Feldman and Chiao in 1971. The mechanism of the interaction of charged particles in intense electromagnetic fields, for example, in the solar corona, had, however, been considered much earlier in astrophysics as the origin of cosmic rays. In this early work, it was shown that in a single pass across the diffraction limited focus of a laser power of 10^{12} W, the electron could gain 30 MeV, and become relativistic within an optical cycle. With a very high transverse velocity ($\boldsymbol{u}$), the magnetic field of the wave (characterized by the magnetic flux density $\boldsymbol{B}$) bends the particle trajectory through $\boldsymbol{u}\times\boldsymbol{B}$ Lorentz force into the direction of the traveling wave. In very large fields, the particle velocity approaches the speed of light and the electron will tend to travel with the wave, gaining energy as it does so.

Figure 1. *Left:* Giant single pulse VULCAN laser. Courtesy: CCLRC Rutherford Appleton Laboratory. *Right:* High-intensity Jena tabletop laser. Courtesy: Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität, Jena

Dramatic improvements in laser technology since 1984 (Figure 2) have revolutionized high-power laser technology. Application of chirped pulse amplification techniques has resulted laser intensities in excess of 10^{19} W cm^{-2}. In 1985, Rhodes discussed the possibility of laser intensities of $\approx 10^{21}$ W cm^{-2}, using a pulse length of 0.1 ps and 1 J of energy. At this intensity, the electric field is 10^{14} V cm^{-1} a value which is over 100 times the Coulomb field binding atomic electrons. In this field, a uranium atom will lose 82 electrons in the short duration of the pulse. The resulting energy density of the pulse is comparable to a 10 keV blackbody (equivalent light pressure $\approx$ 300 Gbar) and comparable to thermonuclear conditions (thermonuclear ignition in DT, i.e. deuterium-tritium mixture, occurs at about 4 keV). In 1988, Boyer et al. first considered the possibility of focusing such lasers onto solid surfaces and cause nuclear transitions. In particular, they showed that by irradiating uranium targets, electro- and photo-fission in the focal region could be induced.

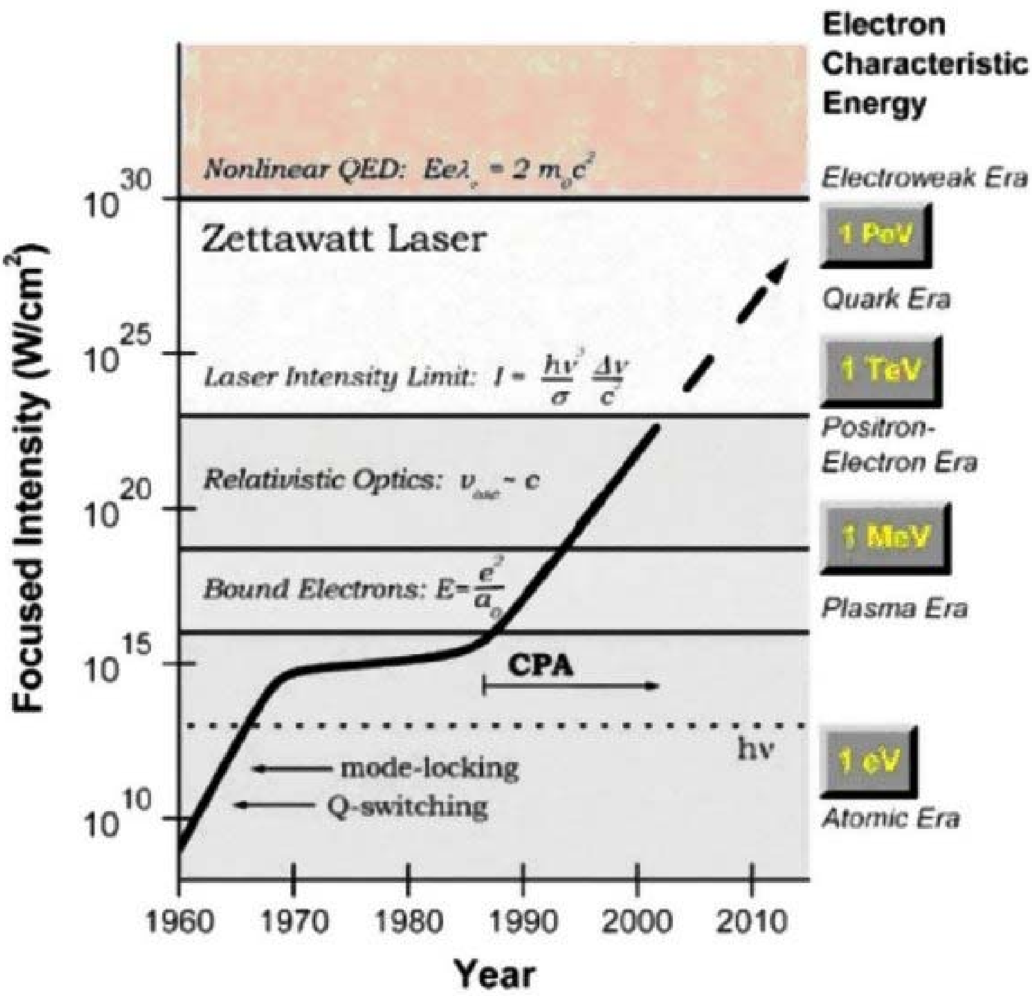

Figure 2. Dramatic increase in the focused laser intensity over the past few decades for tabletop systems. Courtesy Tajima and Mourou (2002). With the development of chirped pulse amplification (CPA) techniques in the mid-eighties, a new era of laser–matter interactions has become possible.

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Biographical Sketch

Joseph Magill is a theoretical physicist and is head of advanced nuclear studies at the European Commission's Joint Research Centre in Karlsruhe, Germany. He received his Ph.D. degree from the University of Glasgow in 1975. His general research interests are in advanced nuclear fuel cycles.

He was a member of the Technical Working group on Accelerators Driven Systems and is one of the authors of the report: "A European Roadmap for Accelerator Driven Systems for Nuclear Waste

Transmutation". He is the author of three books and many articles and patents on nuclear science and has acted as a consultant to the IAEA. He is currently involved in the field of laser nuclear science in which nuclear reactions are induced by lasers – thereby offering a simple and inexpensive way of studying nuclear processes without a nuclear reactor or particle accelerator. His work in this field was selected by PhyscisWeb (http://physicsweb.org/articles/news/7/12/11) as one of the highlights of the year in 2003.

He is the originator of the "Nuclides" products: Nuclides 2000, Nuclides.net and NUCLEONICA. The most recent of these products – NUCLEONICA (www.nucleonica.net) - is a new nuclear science web portal from the European Commission's Joint Research Centre. The portal provides a customizable, integrated environment and collaboration platform for the nuclear sciences using the latest internet "Web 2.0" dynamic technology. The portal is aimed at professionals, academics and students working with radionuclides in fields as diverse as the life sciences (e.g. biology, medicine, agriculture), the earth sciences (geology, meteorology, environmental science) and the more traditional disciplines such as nuclear power, health physics and radiation protection, nuclear and radiochemistry, and astrophysics. It is also used as a knowledge management tool to preserve nuclear knowledge built up over many decades by creating modern web-based versions of so-called legacy computer codes.

Since 2003 he has organized nuclear science training courses based on the use of this internet technology. Recently, he has published the new 7th Edition of the Karlsruhe Nuclide Chart.

Dr. Magill is a member of the Institute of Physics.