OECD Global Science Forum

Workshop on Compact High-Intensity Short-Pulse Lasers: Future Directions and Applications

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Final Report from the Workshop

Table of Contents

A. Background

Since their invention in the early 1960s, lasers have found innumerable applications based on their ability to produce intense, collimated, monochromatic, coherent beams of photons. From the beginning, researchers have sought to increase the peak power of their lasers since, invariably, each increment in power led to new useful applications. As shown in Figure 1, this quest was blocked for about fifteen years, since high intensities were found to affect the optical properties of the lasing materials, resulting in beam instabilities. In 1985, an ingenious technique, "chirped pulse amplification" (CPA) was introduced, and the intensity barrier was eliminated for the case of short-pulse beams[1]. Figure 1 shows that the resulting intensity increases have been dramatic,

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[1] The CPA technique involves a series of creative optical manipulations, as follows. A low-power conventional laser is operated in a special "phase-locked" mode, which produces a series of very short ($\sim 10^{-13}$ s) low-energy pulses, each pulse containing a broad spectrum of component frequencies. These pulses are then stretched in time by a factor of approximately ten thousand, using a pair of diffraction gratings. This decreases the instantaneous power levels by the same amount, allowing the stretched pulses to be optically amplified without encountering non-linearities in the optical medium due to high intensities. In high-peformance systems, the amplification factor can be 10^{10} or higher. Finally, the amplified pulses

and this trend is expected to continue for several more years. Moreover, because the light pulses are emitted at modest repetition rates, the average power levels of the lasers are low. Consequently, there is potential for these devices to be made relatively compact.

The combination of very high peak power and very short pulse duration has opened up a vast new range of unique and exciting applications. When a field of science surges forward in this manner, new challenges and opportunities are created for policy-makers as well as scientists. Recognising this, delegates to the OECD Global Science Forum, acting on a proposal from the delegation of Japan, authorised the convening of a workshop that would bring together researchers and agency programme officials, to review the present status and future prospects of research that uses this new class of high performance lasers.

The workshop was attended by fifty-six government-appointed delegates from ten OECD member countries and four non-member countries, and approximately thirty observers from Japanese laboratories and institutions. It was planned and chaired by Dr. Yoshiaki Kato, with Prof. Danièle Hulin as Vice-Chair, supported by an international Steering Committee of leading scientists. The agenda, and the list of participants (including the members of the Steering Committee) are appended. This report enumerates consensus findings and conclusions that deserve the attention of policy-makers and members of the scientific community as they consider ways of promoting basic and applied research using the new generation of high performance lasers.

B. General Findings about High-Intensity Short-Pulse Lasers

1. High-intensity short-pulse lasers create extreme physical conditions.

   The ability to generate very short, high-intensity pulses of laser radiation leads to the creation of extreme conditions when the pulses are incident on a target. Typical high performance laser parameters are:

   Peak power: ~ 100 terawatts (1 TW = 10^{12} watts)
   Pulse duration: ~ 20 femtoseconds (1 fs = 10^{-15} seconds)
   Pulse energy: ~ 2 Joules
   Repetition rate: ~ 10 Hertz
   Wavelength: ~ 800 nanometres

   With appropriate focussing, pulses impinging on a target can create, during the extremely short pulse duration, the following exotic conditions, never before achieved simultaneously in the laboratory:

   Intensity: 10^{20} watts/cm^2
   Electric field: ~ 10^{11} volts/cm
   Magnetic field: ~ 10^9 gauss (10^5 Tesla)
   Temperature: ~ 10^{10} K (10^6 eV)
   Pressure: ~ 10^9 bars

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are re-compressed in time (again using a pair of gratings) in a way that preserves the phase relationships between the (amplified) component frequencies. This re-creates the original very short pulses, now increased in power by the amplification factor. In high-end systems, severe nonlinearities would definitely occur in the optical medium, so the last step (and any interaction with a target) have to take place in an evacuated chamber.

Acceleration: ~ 10^{26} cm/s^2

Matter that is exposed to these extreme conditions behaves in ways that produce new insights into fundamental phenomena from condensed matter studies (with characteristic energies in the eV range) to nuclear physics, high energy physics, astrophysics, and cosmology (with characteristic energies of MeV and GeV).

2. New cross-disciplinary fields and applications are emerging.

   Some of the observed or predicted effects of the extreme radiation have not been associated with lasers before, for example, the emission and/or acceleration of nuclei and elementary particles, or the generation of coherent X-rays. In some cases, the results are unprecedented and could have a significant impact on the long-term future of well-established fields such as high-energy physics and nuclear physics. Already, scientific communities that have not traditionally interacted are being brought together. While some of the suggested applications may not yet withstand detailed comparison with more conventional solutions, there is a sense among laser researchers that the full potential of the new techniques has yet to be explored and that many exciting discoveries lie ahead. One of the near-term challenges is to develop consultation and collaboration mechanisms for researchers from the hitherto unrelated areas.

3. Further advances in laser performance can be expected.

   While some researchers are exploring novel uses of the current generation of lasers, others are searching for ways to enhance laser performance even further. The following avenues are being explored:

   - Increasing the energy per pulse by improving the performance of the optical amplification system. Currently, two amplification media are most widely used: neodymium glass (Nd:glass) and titanium sapphire (Ti:saphhire) (the latter supports much shorter pulses). New advanced materials and fabrication techniques are being investigated, for example, ytterbium glass and alexandrite. Some of the materials could also support higher pulse repetition rates, thus increasing the average power of the lasers. Highly-efficient solid-state diode lasers could be used to supply the amplification energy.

     The power of the stretched pulses can be raised by increasing the size of the laser while maintaining the energy density at reasonable levels. Indeed, there is probably no inherent limit to the performance increases that can be achieved in this way, although the size and cost of key components (diffraction gratings, mirrors, amplification cells) will impose practical limits.

     Diffraction gratings are one of the main technological bottlenecks. At present, the grating sizes are mainly limited by relatively low radiation damage thresholds. Diffraction efficiency is also a problem: typically, a quarter of the energy is lost in the compressor. Thus, the field needs more efficient diffraction gratings with high damage thresholds. For example, an increase of a factor two in damage threshold efficiency would translate into a decrease of two in the beam area, i.e., smaller and much cheaper optics.

   - Shortening the pulse duration and enhancing pulse contrast. The period of an optical cycle[2] in the near infrared range is approximately 3 fs. A 10 fs pulse, composed of only a few cycles, is thus already near the limit for light of the characteristic laser

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[2] The time needed for a one complete cycle of the electric or magnetic field.

wavelength (approximately 800 nanometres). There is room for improvements through careful control of the phases of the component frequencies of the pulses as they are stretched, amplified and compressed (see footnote 1 above). Another benefit of phase-control techniques is to suppress spurious emissions outside the main pulses. Some ultra high intensity experiments require a high contrast ratio (~10^{10}:1) between peak and background intensities so the main pulse does not interact with an undesirable preformed plasma.

- <u>Decreasing the spot size on the target</u>. The use of actively-deformable mirrors (which are under development in many fields of applied optics) and other techniques for wavefront control, should allow reductions in spot size to the theoretical limit, which is approximately equal to the central wavelength of the laser light.
- <u>Increasing the average power</u>. Presently, most solid state, high-intensity lasers are limited to a few tens of watts of average power, regardless of laser technology and architecture. This is a rather severe limitation that stands in the way of desirable future applications. Considerable effort is under way in several laboratories to overcome this limitation (e.g., diode laser pumping and cryogenic cooling of the amplifying media, as well as development of innovative media where the pumping and lasing frequencies are more closely matched).
- <u>Developing user-friendly systems</u>. At present, the availability of high-intensity short-pulse lasers for a wide range of users and for diverse applications is limited by the necessity of providing experienced support personnel, and the high costs of operation and maintenance. Historically, advanced laser systems have made a successful transition from the specialised laboratory to the scientific marketplace, and this process must now be repeated for a new generation of user-friendly, low-cost, high-intensity short-pulse lasers.

4. Specialised lasers will be developed at different size and performance scales.

While some high-intensity, short-pulse lasers are described as compact (the term "tabletop lasers" is often used) the most advanced systems (100 TW level) are usually implemented on an optical table of about ten metres length. Still, this represents a major decrease in size relative to the very large high energy systems[3] that require big dedicated building complexes. In the future, as the technology progresses and as systems with customised performance characteristics are implemented for different applications, the "tabletop" designation may well become more appropriate. Such lasers, which could become available from commercial manufacturers as "turnkey systems", could become valuable tools in many areas of basic and applied research, providing access to very exotic radiation environments at an affordable price and size scale. Conversely, the most advanced high-intensity short-pulse lasers, in the multi-petawatt power regime, may well grow to the "building size" scale, and may require the kind of physical, technical, and administrative support that characterises true "megascience" projects such as synchrotron radiation storage rings or neutron sources.

5. With lasers, "big science" can be practised in small- and medium-sized laboratories.

The impressive operational parameters of these lasers, combined with their modest cost and size, allow individual university departments and laboratories to practise certain aspects of "big science". This can be especially beneficial to students who, far from large facilities, can

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[3] These very large lasers (such as NOVA, NIF, LMJ) are used for inertial fusion experiments and for national defense applications. They differ in many significant ways from the devices described in this report.

find themselves involved in cutting-edge research with exotic beams while remaining in control of their small- or medium-scale experiments. Also, because of their small size, high peak power systems can be relatively easily added to existing (or planned) large facilities such as electron accelerators and storage rings.

6. The highest-intensity lasers may become user facilities.

   The number of high performance lasers and the size of the scientific community have increased rapidly. At the highest power levels (100 TW and higher), there are currently eight systems world-wide (two each in Japan, US, France, and one each in the United Kingdom and Germany). At least one of the large installations functions as a user facility, accepting proposals for use of the laser beams by external researchers. There are many informal international contacts among the researchers, and numerous technical conferences and workshops - at least 10 per year. Because the field is so new, however, there is no major dedicated conference or publication devoted exclusively to high-intensity short-pulse lasers, and there are few formal international co-operative agreements between laboratories or funding agencies.

7. High field science is gaining in importance and popularity.

   In a short period of time the field has demonstrated great progress and vitality. All large-scale laser fusion facilities in the world have reconfigured their nanosecond lasers into short-pulse high-intensity lasers. The number of scientists is of the order of one thousand (including graduate students). The number of publications in major scientific journals is greater than one thousand (more than 500 for high harmonics alone). On average, one article in Physical Review Letters per weekly issue is devoted to high field science. In the United Kingdom, the Institute of Physics surveyed physicists regarding their choices for the most promising areas of physics, and high intensity research emerged as the top choice.

C. General Conclusions of the Workshop

<u>For governments:</u>

1. Systematic support is needed for laser development and applications.

   Given that photons are an extremely useful probe for studying the structure and dynamics of condensed matter (including biological matter) policymakers are encouraged to examine long-term needs and plans regarding high-intensity photon sources. Particular attention should be devoted to two innovative techniques that, given the appropriate level of support, can deliver vastly enhanced performance in the next 5 to 10 years: (1) high-intensity short-pulse lasers as considered in the Global Science Forum workshop and as described in this report, and (2) linac-based free electron lasers (FELs).

   The dramatic rise in performance of high-intensity short-pulse lasers, the emergence of many new applications, and the increase in the number of facilities, projects and researchers, justify the identification of this line of research as a scientific field in its own right. Accordingly, policymakers may wish to adopt measures in planning, administration and funding to systematically promote progress in the field, and to ensure maximum benefits across a broad spectrum of basic and applied research. Given that the full potential of these lasers is not yet known (and has certainly not been achieved) systematic targeted support could be provided in two directions: (1) further enhancements in performance as measured by critical parameters: intensity, average power, pulse duration, wavelength and size; and (2) investigation of innovative applications, including, but not limited to, those enumerated in Section D of this report.

2. Large-scale facilities offer advantages at the highest laser performance levels.

   Large-scale facilities for research using high-intensity short-pulse lasers can be an integral part of an optimal national or regional science policy. These facilities, while costly, provide the physical infrastructure, technical and administrative support, and an intellectual environment that supports exploration of the outer performance limits of the lasers. They also provide a venue for exchange of ideas across diverse applications, enhanced international co-operation, and user-mode operation that attracts academic and industry scientists from outside the laser community. Governments should consider the development of large-scale national and regional facilities as part of their overall science policies. At some future time, it may be appropriate to consider establishing a globally-funded large-scale facility for state-of-the-art lasers and applications. The case for such a project could be investigated by members of the scientific community.

<u>For the scientific community:</u>

1. Co-ordination mechanisms in the community should be strengthened.

   The community should seek a stronger unity and sense of identity by adopting a more systematic approach to its own internal organisation on a global scale, and by more actively publicising new results. The community should consider actions that would allow it to:

   - Rationalise and consolidate existing meetings and workshops, and create a dedicated venue for discussions on the science and technology of high-intensity lasers and their applications. This venue could be used to promote discussions among researchers in different fields where lasers are not currently used, but which could benefit from the new levels of performance that are being achieved with terawatt- and petawatt-scale short-pulse lasers.
   - Create a process through which laboratory directors and program managers could discuss international co-operative activities such as dividing tasks among laboratories, joint development or procurement of critical components for advanced laser systems, exchanges of personnel and equipment, etc.
   - Provide an opportunity for agency officials and programme managers to review the overall status of the field, to understand the needs and concerns of researchers, and to learn about promising new lines of research.
   - Attract more students to work and stay in the field, and promote their interactions with prominent scientists on an international level, thereby familiarising the students with the latest results and techniques.

   While there was broad agreement among workshop participants that the high-intensity short-pulse laser community would benefit from an enhanced unity and identity, the exact mechanism to achieve the above goals has not been determined; in particular, whether the goals could be achieved under the aegis of an existing structure, or whether a new mechanism was needed. Participants agreed to reflect and consult on these issues.

D. Applications of High-Intensity Short-Pulse Lasers: Specific Findings and Conclusions

1. Atomic and Molecular Physics

The interaction of light with atoms and molecules occurs through the coupling of the light wave to electrons, free or bound. In the case of high-intensity short-pulse lasers, new effects arise due to the enormous energy absorbed by the electrons, which is then transformed through a wide range of mechanisms into kinetic energy of heavier particles, into internal degrees of freedom of molecules and clusters (or even nuclei), into collective motion of charged particles in plasmas, or into the directed or isotropic emission of energetic photons, neutrons, protons or electrons. It is these new effects which lay the foundation for novel applications.

There are four basic types of high-intensity light-matter interaction: a) creation of free electrons through various ionisation mechanisms (tunnelling, field ionisation or multi-photon absorption, depending on the light frequency and the tunnelling time); b) fragmentation of molecules and small compounds; c) the motion of free particles (predominantly electrons) in the laser field, which may, above 10^{18} W/cm^2, be accompanied or dominated by relativistic effects; and d) collective effects in light-driven plasmas which are the basis for most other applications in nuclear physics and X-ray generation.

With light in the 1000 nanometre wavelength range and an intensity of 10^{20} W/cm^2, up to some 30 electrons can be liberated through ionisation. The complete stripping of uranium atoms ($Z = 92$) would require intensities of the order of 10^{24} W/cm^2, well beyond today's capabilities. Fragmentation of molecules and small clusters is a more complicated process and is highly dependent on the species under investigation. It is usually initiated by ionisation, and followed by dissociation and fragmentation processes. Here the pulse duration plays an important role, leading to Coulomb explosion in the case of very short (femtoseconds) pulses, statistical fragmentation involving vibrational degrees of freedom at about 100 fs, or plasma-type heating and expansion in the case of even longer pulses. Research on light-matter interactions at high intensities with molecules and clusters provides enormous opportunities for basic research and applications.

The study of the relativistic motions of free electrons under the influence of high-intensity light waves could lead to the development of novel short wavelength light sources, or applications based on quantum electrodynamics (QED) effects (e.g., pair production in the presence of charged particles, which has already been observed). However, the most important and scientifically challenging effects arise from the combined and collective motion of electrons and ions in plasmas, leading to additional energy absorption from the light field and, thus, novel physical effects and applications. One of the most important of these effects is the generation of short wavelength photons. High-power femtosecond lasers could be used to generate coherent ultrashort VUV/X-ray radiation (high-order harmonics, X-ray lasers) or incoherent ultrashort VUV/X-ray radiation (laser-produced plasmas, laser-driven inner-shell transitions). These light sources could find applications in molecular imaging, gas-phase chemical reactions, solid-state physics, dynamic structural analysis of biological materials, nonlinear optics, time-resolved core-level spectroscopy, ultrashort time-resolution X-ray diffraction and absorption spectroscopy, and photoelectron or Auger electron spectroscopy in organic and inorganic materials. However, for these unique light sources to become practical, significant technical challenges will have to be overcome, for example, increasing conversion efficiency, and extending wavelength coverage below 1 nm. In the long term, it is conceivable that compact high-power, long-wavelength lasers could replace accelerators as drivers of free electron lasers, thus opening up entirely new research opportunities.

2. Biology

In most instances, fragile biological samples do not lend themselves to study using ultrahigh intensity sources. There are a number of promising applications, however, that take advantage of the high intensity and the short duration of laser pulses.

As part of “post-genomics” research, measurements of the structure and dynamics of proteins are essential for understanding phenomena such as protein folding, protein functioning, or specific molecular recognition. Structural analyses of reaction intermediates and short-lived conformational states are also important topics in structural biology. The major obstacle to high-throughput structural analyses of large numbers of proteins (structural genomics) is the necessity of producing crystals for X-ray diffraction measurements. The availability of very high intensity X-ray pulses offers the prospect of imaging single protein molecules, which would have the additional advantage of avoiding changes in protein structure caused by crystallisation. X-rays produced using high-intensity short-pulse lasers, and those produced by the coming generation of accelerator-based free electron lasers, may lead to the desired breakthrough in structural genomics. The key desirable characteristic of these sources is that they will produce very short pulses (in the femtosecond range) that will produce a measurable amount of diffracted photons before the disintegration of the molecule.

Femtosecond incoherent plasma-based X-ray pulses can be produced through the irradiation of different targets by intense femtosecond laser pulses, and these X-ray pulses can be used for spectroscopy or microscopy. Time-resolved diffraction of laser-produced X-rays provides information about atomic displacements and the tracing of reaction paths following excitation. The identification of conformational changes should lead to a better knowledge of reaction inhibitors and drug candidates.

As described below, lasers can generate diagnostic neutrons for probing soft tissues (they have a higher cross section than X-rays for light elements). Similarly, laser-based proton and ion therapy is an emerging and promising domain.

3. Neutron Science

In recent years, researchers have demonstrated a variety of ways of producing neutron bursts from intense laser pulses focused onto solid targets or targets of atomic clusters. Most of these approaches use the laser to create a burst of neutrons from fusion reactions in the hot plasma. While still somewhat speculative, it appears that laser-driven fusion neutron sources could be scaled to high enough neutron fluxes to be useful as a stand-alone neutron sources.

Perhaps the most promising application of such neutron sources will be the study of radiation damage to materials. Understanding how fusion neutrons damage materials is needed to surmount one of the principal barriers to the ultimate success of nuclear fusion as a viable source of energy, since the walls of any future fusion reactor will be exposed to enormous neutron fluxes. Such materials research, to date, has been hindered by the lack of suitable high flux fusion neutron sources. A laser driven source, even if it produced a modest number of neutrons, would be able to focus the beam to a very small size, thus allowing the exposure of small samples to very high fluxes.

Laser-driven neutron sources could have both technological as well as basic science applications. For example, it might be possible to utilise the very short timescale of the neutron burst to perform pump-probe experiments, i.e., to study the time dynamics of radiation damage on the microscopic scale. This class of time-resolved experiments is not possible with any other existing or proposed neutron source.

4. Nuclear Physics

Intensities in the 10^{21} W/cm^2 range produce plasma conditions unlike any previously generated in the laboratory. Electric fields about 100 times stronger than the field that binds electrons to atomic nuclei are produced, and these can generate plasma waves that can trap electrons and accelerate them to high energies within just a few centimetres, instead of kilometres as in conventional particle accelerators. These electrons interact with the target medium to produce energetic γ radiation which may in turn induce photo-nuclear reactions including fission, the production of proton-rich isotopes and, potentially, pion emission. Intense beams of energetic protons (and highly-charged ions) are produced, with likely applications in medicine, e.g., in proton oncology and in the production of short-lived isotopes (e.g. ^{11}C, ^{13}N, ^{15}O, ^{18}F) for positron emission tomography (PET).

It is anticipated that laser intensities up to 10^{21-23} W/cm^{-2} will become possible in the foreseeable future. At these extreme intensities electrons can be accelerated to 100 GeV, directly affecting nuclear energy levels, and, for the first time in a laboratory, replicating conditions inside supernovae or in the vicinity of black holes.

5. Fusion Energy Research

Large high-power lasers are being developed for research on inertially-confined fusion energy (IFE). In this approach, multiple high-energy beams rapidly heat the surface of a spherical target of deuterium and tritium, forming a plasma corona around it. The surface material is blown off and the fuel is compressed such that a hot dense central core is created. The fuel ignites and a thermonuclear burn wave spreads throughout the compressed material. The stringent conditions required for this process have proven to be a major impediment to IFE source development, but they may be relaxed by the proposed use of additional high-intensity laser pulses in a technique called “fast-ignition”. The intense pulses, incident on a fuel pellet, would generate large quantities of energetic electrons and protons which could rapidly heat a small region on the periphery of the compressed core to over 100 million K. The resulting fusion burn could propagate from this small volume on the edge of the core, and throughout the remaining fuel before hydrodynamic disassembly of the core.

Much of the detail of the physics involved in fast-ignition remains unexplored, and considerable progress is expected in the near future as the intensities and energies of laser pulses continue to increase.

6. High-Field Science

High-field science involves studies in the domain where very high electromagnetic fields cause electrons to oscillate with velocities comparable to the speed of light. These conditions are reached when the laser intensity is of the order of 10^{18} W/cm^2 for a typical optical frequency of the laser. In recent years experimenters who are exploring this new domain have encountered a variety of impressive novel phenomena, such as electron acceleration beyond 100 MeV, ion acceleration beyond tens of MeV (with a 1 TV/m accelerating field), nuclear transmutation, positron generation, highly stripped high-Z atoms, hot ions that generate copious numbers of neutrons, and very intense magnetic fields. Further increases in intensity may allow the study of an even wider range of exotic phenomena that are currently inaccessible in the laboratory. The following is an enumeration of some of the salient phenomena in these regimes.

A. Regime of 10^{21}-10^{22} W/cm^2
  - electron accelerator and injector with > GeV energies (and low transverse emittance)
  - proton acceleration and sources with > 100 MeV energies (and low transverse emittance)
  - ion acceleration and sources with energies >> 100 MeV
  - X-rays as Larmor radiation[4], coherent X-rays, and X-rays from clusters
  - neutron sources by cluster-laser irradiation
  - gamma-rays up to GeV energies with high fluence
  - extremely high magnetic fields of ~ 10^9 gauss (10^5 Tesla)
  - deeply- or fully-stripped high-Z nuclei leading to nuclear instabilities
  - instantaneous extreme high pressure states

B. Regime of 10^{23}-10^{24} W/cm^2
  - electrons beyond TeV energies
  - protons with > GeV energies
  - hot matter with temperature/energy > GeV: laser nuclear physics, quark-gluon plasma
  - intense Larmor radiation (X-rays)
  - significant Unruh radiation[5]: test of horizon physics
  - nonlinear and collective QED in the presence of nuclei

C. Regime of 10^{25} -10^{26} W/cm^2
  - ultrarelativistic protons
  - prompt acceleration of unstable particles such as pions and muons
  - relativistic flow of matter
  - horizon physics with extreme acceleration: extra-dimensions in quantum gravity
  - photon/photon (gamma/gamma) interactions

7. High-Energy Physics

A very promising application of lasers for high-energy physics is a gamma-gamma (and/or gamma-electron) collider in the energy range from hundreds of GeV to several TeV. High energy photons could be produced via Compton scattering of laser light from high energy electrons produced by a linear accelerator. After scattering, the photons would have an energy close to that of the initial electrons and would follow their direction to the collider interaction point. Using a laser with a flash energy of several Joules one could “convert” almost all of the electrons to high energy photons, and thus obtain colliding gamma-gamma and gamma-electron

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[4] Electrons oscillating in an optical field at relativistic intensities are strongly accelerated in the laser propagation (forward) direction, emitting intense X-ray radiation in that direction with an annular intensity distribution.

[5] This radiation, heretofore unobserved, is expected to occur at extermely high accelerations. The study of its properties would shed light on the relationship between quantum physics and general relativity, which is considered by many to be one of the most fundamental and difficult problems in contemporary science.

beams with high energy and luminosity. Such an option has been included in all projects for linear colliders which are the prime candidates for the next global-scale big project in particle physics. The physics potential of a photon collider is very rich and complements in an essential way the physics program of the electron-positron mode. The needed laser system (5 J diffraction-limited pulse, 1 ps duration, 1 μm wavelength, 15 kHz repetition rate) would require diode pumping, adaptive optics and other advanced techniques. Its development would be very challenging, requiring close co-operation of accelerator and laser experts.

New connections are being established between high intensity laser physics and astrophysics. Frequently, scaling over many orders of magnitude is required, but the basic physics and computer modelling (e.g., relativistic plasmas, instabilities) are the same. Here joint conferences are foreseen, to move beyond some of the already-recognised topics such as Rayleigh-Taylor instabilities, supernova vs. pellet explosions, or acceleration of particles to very high energies.

8. X-ray imaging

When sub-picosecond terawatt laser pulses are focused onto solid targets of high-Z materials, intense X-ray radiation can be produced. In contrast to the situation when nanosecond pulses are employed, there is practically no time for the formation of an expanding plasma to shield off the main part of the impinging pulse. Thus, femtosecond laser pulses may lead to the formation of extremely dense plasmas of very small size. These plasmas radiate at all wavelengths, including hard X-rays. The use of these intense pulses of laser-produced hard X-rays offers novel possibilities for medical imaging, compared to the X-ray tubes used routinely in most hospitals. This precision will also find important industrial applications for quality control such as crack inspection to detect local discontinuities, porosity, slag inclusions, shrinkage defects, cold shuts, and voids.

With lasers, the X-ray source size can be made extremely small (<10 micrometres). In conventional X-ray tubes, the source size is essentially space-charge limited and therefore significantly larger. This small source size allows radiography with unprecedented spatial resolution (micrometres) using high-resolution imaging detectors. Alternatively, the small source size allows conventional imaging detectors to be used in a high magnification geometry. However, radiography is essentially the making of a shadow of, e.g., the bones in a body. For a given detector sensitivity, large magnification requires a great increase in X-ray flux and consequently increased radiation hazards. Although applications on humans seldom (or never) justify an increased dose, there could be important applications in small-animal radiography and micro computer-aided tomography. The need to resolve small features requires high spatial resolution that can be naturally provided by tightly focused ultrashort pulses.

The extremely short pulse duration of laser-produced hard X-rays can be utilised for gated viewing through tissue, to eliminate blurring of the image by scattered radiation. This technique allows increased contrast for a given X-ray dose, or - more importantly - the absorbed dose can be reduced while maintaining image quality. Proof-of-principle experiments have been performed to demonstrate this effect, including tomography. The future of these techniques is strongly coupled to the potential development of efficient gateable imaging X-ray detectors. The average power and user friendliness of compact femtosecond terawatt lasers also need to be significantly increased if these techniques are to become realistic alternatives to conventional methods.

Laser-produced X-rays can also be employed for differential absorption imaging of contrast agents. Such techniques, now performed on a small scale using synchrotron radiation, have also been demonstrated with a laser-based source in proof-of-principle experiments.

The ultrashort pulse duration of laser-produced X-rays leads to extremely high dose rates - 10 orders of magnitude higher than with conventionally X-rays tubes. This might be expected to give an increased radiation hazard. However, it has been established in cell culture experiments that, for a given dose, the hazard is similar to that of a conventional source.

9. Cancer Therapy

High-intensity short laser pulses, when incident on a solid target, can generate beams of protons and ions. The possibility of using these particles to destroy cancer tumours is now the subject of intense interest. The goal of radiation therapy is to maximise the tumour dose without harming surrounding healthy tissues. Ions have a well-defined range in tissue with minimal lateral scattering and a maximum dose deposition at the end of the track. Thus, the use of heavy particles in radiotherapy is motivated by a superior accuracy in the spatial dose distribution in the human body for deep seated tumours compared to photons and electrons. When treating tumours in such sensitive areas as the brain or the spinal cord, the ability to deposit controlled amounts of energy using heavy particles in small, well-defined areas is critical.

Clinical trials using proton and carbon beams are under way in several countries. One of the chief obstacles to wide-scale use of particle-based therapy, however, is the large cost of the accelerators (cyclotrons and synchrotrons). For example, the Heavy Ion Medical Accelerator (HIMAC) in Chiba, Japan, had a construction cost of almost 300 million dollars[6]. It can treat about 200 patients a year - a small fraction of cases that could benefit from this form of cancer therapy.

Motivated by a desire to reduce the size and cost of radiotherapy facilities, researchers in Japan are setting out to combine a 100TW, 20fs laser with a special purpose pulsed synchrotron that will accelerate carbon ions. The ultimate goal of this effort is to produce a device that can be installed in a hospital, with a reduction in size by an order of magnitude, and in cost by a factor of five compared with existing devices.

10. Atmospheric Science

Following demonstrations that a focused beam of terawatt laser pulses induces ionisation and channelling in air leading to the formation of a long-range broad-band distributed emitting region, laser-radar experiments with a terawatt laser source have been performed. Range-resolved detection of molecular atmospheric species has been demonstrated. Further, such beams can be used to trigger electric discharges and could be important in research on lightening. A mobile terawatt laser system for experiments of the lidar type has already been implemented as European collaboration.

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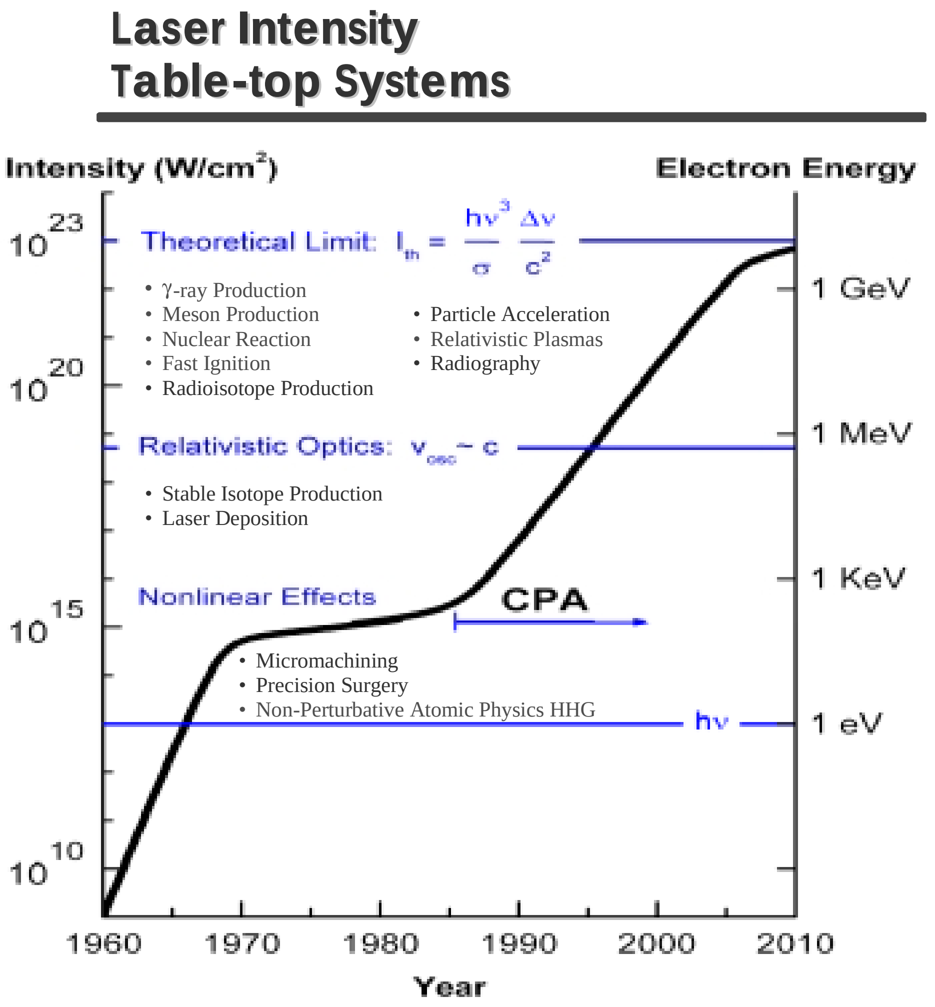
[6] This figure includes infrastructure costs (building, etc).



<u>Figure 1. The evolution of laser intensity to the present and beyond.</u>
The significance of the introduction of the CPA technique in the mid-eighties is clearly shown. By physically scaling up the laser systems, much higher intensities could be reached during the next 10-20 years. The right-hand vertical scale deserves particular attention: it shows the energy acquired by electrons in a target during their interaction with the laser field. In the past 30 years, it has increased from eV to GeV (the typical energy of today’s synchrotrons). The figure shows that the current increases in intensity are similar to those of first decade following the invention of the laser itself. That event marked the beginning of the important and successful field of Nonlinear Optics. Today, laser intensities are entering into new physical regimes, allowing the observation of novel phenomena in such fields as nuclear physics, high energy physics, astrophysics, and cosmology. This is, in effect, the “second wind” of Nonlinear Optics.

Workshop on Compact High-Intensity Short-Pulse Lasers: Future Directions and Applications

Participants

Chairman	**Dr. Yoshiaki Kato***	
Austria	Prof. Christian Spielmann*	
Brazil	Dr. Nilson Dias Vieira Jr. *	
Denmark	Dr. Paul Michael Petersen	
France	**Dr. Danièle Hulin***	Dr. J.P. Chambaret*
	Dr. F. Kovacs	Dr. Pierre Chavel
	Dr. Denis Perret Gallix	
Germany	**Prof. Wolfgang Sandner***	Dr.-Ing. Stefan Altmeyer
	Prof. Roland Sauerbrey*	Prof. G. Materlik*
	Prof. Dietrich Habs*	
Israel	Prof. Arie Zigler*	
Italy	Prof. Sandro De Silvestri*	
Japan	Mr. Toichi Sakata	Prof. Kunioki Mima*
	Dr. Shinzo Saito	Prof. Hideaki Takabe*
	Dr. Yukio Sato	Dr. Junetsu Mizoe*
	Dr. Takashi Arisawa	Prof. Akira Noda*
	Dr. Chiyoe Yamanaka	Dr. Katsumi Midorikawa
	Prof. Shuntaro Watanabe*	Prof. Kenichi Kondo
	Prof. Kaoru Yamanouchi*	Prof. Kenzo Miyazaki
	Prof. Mitsuru Uesaka*	Prof. Tatsuhiko Yamanaka
	Prof. Mikio Kataoka*	Dr. Ryoichi Hajima*
Korea	**Prof. Chang Hee Nam***	Dr. Yong-Joo Rhee
	Dr. Hong Young Kim	
OECD	**Dr. Stefan Michalowski**	Mr. Kenji Sudo
	Dr. Michael W. Oborne	
Russia	Prof. Valery I. Telnov*	
South Africa	Dr. Philemon Mjwara	Prof. Hubertus von Bergmann
Sweden	**Prof. Claes-Göran Wahlström*** (representing Prof. Sune Svanberg in the Steering Committee)	
United Kingdom	**Prof. Henry Hutchinson***	Dr. George Stirling
	Prof. Kenneth W.D. Ledingham*	Dr. Ian Ross*
United States	**Prof. Gerard A. Mourou***	**Prof. Todd Ditmire***
	Prof. C. K. Rhodes*	Prof. Donald Umstadter*
	Prof. Toshiki Tajima*	Dr. Christopher P. J. Barty*
	Dr. William A. Blanpied	Mr. James H. Hall

Bold: Steering Committee Members
* Speakers

Workshop on Compact High-Intensity Short-Pulse Lasers: Future Directions and Applications

Program (Note: Titles of the presentations indicate approximate scopes of the talks.)

May 28, Monday

1. Welcome
   1) JAERI: S. Saito (Vice President, JAERI)
   2) OECD: M. Oborne (Deputy Director for Science, Technology and Industry, OECD)
   3) MEXT: T. Sakata (Deputy Director-General, Research Promotion Bureau, Ministry of Education, Culture, Sports, Science and Technology)

2. Scope of the Workshop
   1) Scope of the workshop: D. Hulin (LOA, France)
   2) Introduction to ultrashort pulse lasers: Y. Kato (JAERI, Japan)
   3) Perspective of ultra-intense laser research (1): G. Mourou (CUOS, Michigan, USA)
   4) Perspective of ultra-intense laser research (2): W. Sandner (Max-Born-Institute, Germany)

3. Future prospect of ultrashort pulse lasers
   1) The state-of-the-art of ultrashort pulse lasers: J. P. Chambaret (LOA, France)
   2) New approach toward ultrahigh power generation: I. Ross (RAL, UK)
   3) Development of high power lasers for science and industry: R. Sauerbrey (U. Jena, Germany)

4. Ultrafast Science
   1) Atto-second physics: C. Spielmann (Technische U., Austria)
   2) Dynamics of Molecules in Intense Laser-light Fields: New Research Directions: K. Yamanouchi (U. Tokyo, Japan)
   3) Structural dynamics with ultrashort pulse X-rays: M. Uesaka (U. Tokyo, Japan)

5. The next generation high brightness/ ultrashort pulse X-ray sources
   1) Ultrabright Xe(L) ~ 2.9 Angstroms X-Ray Source: C. K. Rhodes (U. Illinois at Chicago, USA)
   2) X-ray free electron laser: G. Materlick (DESY, Germany)
   3) Structural biology with high brightness synchrotron sources: M. Kataoka (Nara Inst. S&T, Japan)
   4) VUV coherent source with high-order harmonics: C.-H. Nam (KAIST, Korea)

6. Laboratory Tour of the Advanced Photon Research Center

May 29, Tuesday

7. New developments in nuclear physics with high intensity lasers
   1) Intense, pulsed neutron source with high intensity lasers: T. Ditmire (U. Texas, USA)
   2) Nuclear physics with high intensity lasers: K. W. D. Ledingham (U. Glasgow, UK)
   3) Relativistic laser plasmas and their application to nuclear science: K. Mima (ILE Osaka U., Japan)

8. Advanced accelerators using lasers for future high energy physics
   1) Ultrastrong field physics with very high-intensity lasers: T. Tajima (U. Texas, USA)
   2) Quest for advanced accelerators: D. Habs (U. Munich and CERN, Germany)
   3) Future Compton colliders: V. Telnov (DESY, Germany)
   4) Astrophysics and Advanced Science with Intense Lasers: H. Takabe (ILE Osaka U., Japan)

9. Medical and industrial applications of high intensity lasers
   1) Medical diagnostics with laser-produced X-rays: C.-G. Wahlstrom, Lund Inst. Tech. (Sweden)
   2) Cancer therapy with ion synchrotron accelerators
   3) Fast ion generation with compact lasers: D. Umstadter (CUOS, Michigan, USA)
   4) Development of a compact ion accelerator dedicated for cancer therapy with use of a laser ion source: A. Noda (Kyoto U., Japan)

10. Global Activities on High Intensity Lasers
    1) Evolution toward “Users facility” role : H. Hutchinson (RAL, UK)
    2) Mechanisms of international co-ordination and co-operation: T. Ditmire (U. Texas, USA)
    3) Long-term prospect and future directions: C. P. J. Barty (LLNL, USA)

11. Conclusions and outline of a report to GSF: Y. Kato and D. Hulin

May 30, Wednesday

12. Presentations on Activities on Ultrashort Pulse, High Intensity Lasers in OECD and non-OECD Countries
    1) High-intensity Laser programme at the Rutherford Appleton Laboratory: M. H. R. Hutchinson (RAL, UK)
    2) Research on relativistic dynamics and x-ray generation at MBI Berlin: Wolfgang Sandner (MBI, Germany):
    3) High repetition rate, high peak power lasers and their applications to solid state physics: Shuntaro Watanabe (ISSP, University of Tokyo, Japan)
    4) High peak power few optical cycle laser pulses: generation, characterization and applications: Sandro De Silvestri (Politecnico de Milano, Italy):
    5) Generation of intense few-cycle pulses in an FEL oscillator: Ryoichi Hajima (JAERI, Japan):
    6) Generation of tunable and powerful THz radiation: Arie Zigler (Racah Institute of Physics, Israel)
    7) Laser Research in Brazil: Nilson Dias Vieira, Jr. (Center for Lasers and Applications, San Paulo, Brazil)

13. Laboratory Directors Meeting for Information Exchanges and Follow-on Activities.