Applications of terawatt lasers

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APPLICATIONS OF TERAWATT LASERS

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ABSTRACT

Experiments using high-power laser radiation have recently become much more feasible through the development of chirped pulse amplification. By using titanium sapphire as the gain medium, very compact and high-repetition rate systems reaching terawatt power levels can be constructed. Within the newly established Lund High Power Laser Facility we operate such a system (150 fs, 1.5 TW, 10 Hz, tunable 760-840 nm), which is being employed in a number of basic and applied studies requiring high optical powers. Detailed studies of high-harmonic generation in inert gases are reported as well as the generation of hard X-rays from microplasmas. Ultrasharp medical imaging has been achieved. Intense white-light generation by self-phase modulation in water has been used for biological tissue studies and for photon migration studies in green leaves.

INTRODUCTION

Chirped pulse amplification[1] is a new technique to achieve ultra-high optical powers in compact laser systems. The technique was first used for Nd:Glass amplifier systems, that, however, are restricted to low repetition rates. Titanium sapphire (Ti:S), which is a broadband gain material, allows the generation of shorter pulses (~100 fs) and 10 Hz systems, operating at the terawatt power level can be constructed, also incorporating a certain wavelength tunability. This technology makes high-power experiments readily accessible, with the convenience typical of normal laboratory 10 Hz systems. Different types of high-power experiments are exemplified below:

- Atomic physics at high optical field strengths (10^{10} V/cm $\Leftrightarrow$ 10^{18} W/cm^2)
- High harmonic generation in jets of inert gases, yielding coherent soft X-rays
- Above-threshold ionization (ATI) experiments (multi-photon ionization)
- Generation of broadband X-rays from a solid-density plasma
- X-ray laser pumping, especially photo pumping
- Ps/fs white-light generation with applications in chemistry, biology and medicine

TERAWATT LASERS

During the last few years compact terawatt lasers, sometimes called T^3 (table-top terawatt) systems, based on chirped-pulse amplification have been constructed at various laboratories. Through the introduction of Ti:S in such systems[2,3], particularly convenient systems can be accomplished. This material can readily be pumped by frequency doubled Nd:YAG radiation at 532 nm. The material has a wide gain profile and thus can support amplification of ultrashort pulses (~100 fs), which results in lower pulse-energy demands for reaching terawatt power levels. The thermal properties allow a 10 Hz repetition rate. Within the newly established Lund High Power Laser Facility[4], we operate such a system (Fig. 1), which was developed by a commercial company (Continuum Inc.), with system configuration and performance according to our specifications.

The Lund terawatt laser system employs an Ar^+-laser-pumped Kerr-lens mode locked Ti:S oscillator (Coherent Mira) generating 100 fs nearly transform-limited pulses, that are temporally stretched by a factor of 2500 before injection in a regenerative Ti:S amplifier. After 12 double passes and 10^6 times amplification, final power boosting is performed in a multi-pass Ti:S stage to reach a level of 400 mJ. Two frequency-doubled high-energy Nd:YAG lasers (Continuum NY82) pump the amplifiers at a total energy level of 1.3 J at 10 Hz. After beam expansion to 50 mm and pulse compression in two parallel, 11 x 11 cm gold coated holographic gratings with 1800 groves/mm, 150 fs pulses of powers up to 1.5 TW can be obtained in the 760-840 nm region. To avoid phase-distortions (B-integral pick-up) and associated beam degradation, the beam can be propagated in beam transport tubes and mirror chambers, that presently can be filled with Ar and which for the future will be evacuated. In order to characterize the system, the oscillator output is analyzed spectrally with an OMA system and temporally with a scanning autocorrelator. The final output beacan be analyzed with a single-shot autocorrelator and a ccd beam profiler. The system is now being used in many applications.

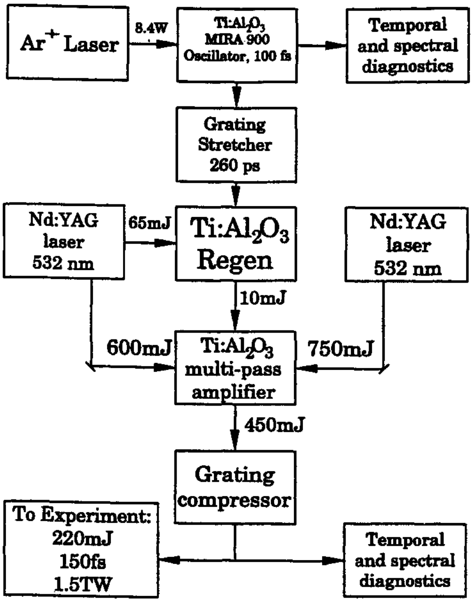


Fig. 1. Basic scheme for the Lund terawatt laser

HIGH HARMONIC GENERATION

High-harmonic generation gives easy access to coherent XUV and soft X-ray radiation for various applications, including short-wavelength holography. Harmonics up till the 93rd (limited by analyzing spectrometer) in inert-gas jets have been generated and studied. The experimintal set-up for the detection of high harmonics is shown in Fig. 2. The laser light is focussed by an f=1 or 2 m lens into a pulsed jet of inert gas at a density corresponding to typically 20 torr or $7x10^{17}$ atoms/cm^3. The generated radiation is analyzed on axis by a monochromator incorporating a toroidal mirror and a 700 grooves/mm plane grating, both coated with gold. As a detector an electron multiplier was used. Higher harmonic orders have been observed[5,6], but the present study allowed a very detailed investigation of intensity dependence, plateau cut-off behaviour and spectral shifts for He, Ne, Ar and Xe[7,8]. Harmonics from the 51st to the 93rd are shown for He in Fig. 3. The intensity dependence of the generation efficiency for the 15th harmonic in Ar is shown in Fig. 4. For low laser intensities the harmonic yield increases very rapidly up to a cut-off point, beyond which the harmonic intensity varies much more slowly. Finally, saturation corresponding to ionization occurs. The photon energy for plateau cut-off was found to follow the law $I_p + 2.4\ U_p$, where I_p is the ionization potential of the inert gas and $U_p = e^2E^2/4m\omega^2$ is the ponderomotive potential[9]. Such an expression nicely fitting the experimental data is shown for neon in Fig. 5. On a lower-power system the temporal behaviour of lower harmonics has been investigated employing a fast streak camera.

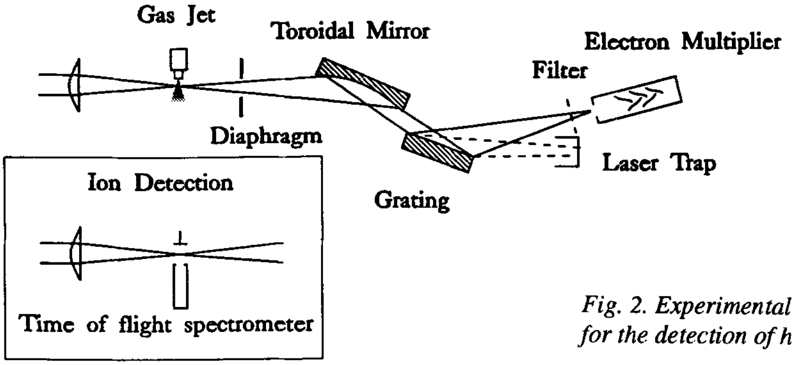
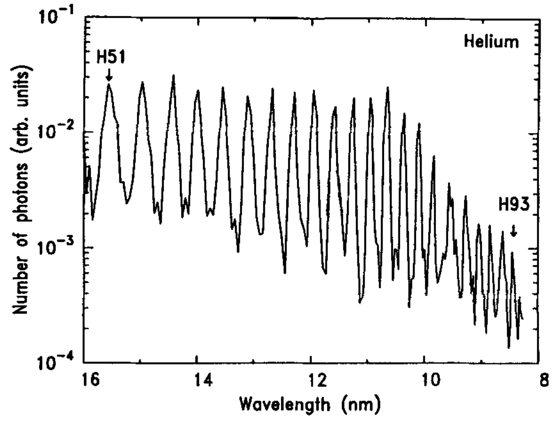


Fig. 2. Experimental arrangement for the detection of high harmonics



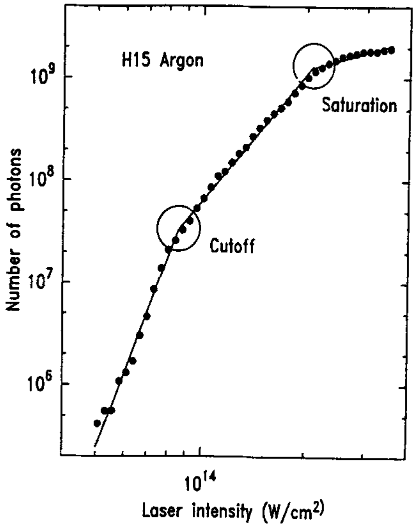


Fig. 3. Recording of high harmonics in helium (top)
Fig. 4. Intensity dependence of the 15th harmonic in argon (right)

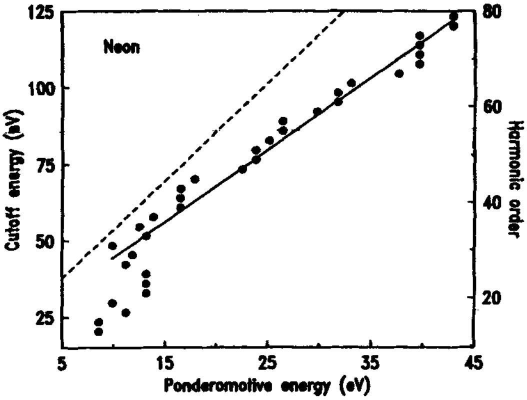


Fig. 5. Cut off energy as a function of the ponderomotive energy U_p. The solid line is a linear best fit: $I_p(Ne) + 2.4U_p$, while the dashed line corresponds to the single atom response $I_p(Ne) + 3.2\, U_p$[10].

X-RAY GENERATION AND APPLICATION

By focussing sub-picosecond terawatt pulses on solid targets, intense X-ray radiation can be obtained. It has been shown that photon energies approaching MeV can be obtained[11]. We have demonstrated medical imaging on standard image plates using this source[12]. The extremely small source size allows magnification radiography (x80 magnification demonstrated). Single-pulse (10^{-12} s) image recording was also feasible. The experimental set up and an X-ray image are shown in Figs. 6 and 7. The spectral content of the radiation is now being studied using nuclear physics instrumentation. Laser-produced plasmas from irradiated liquid droplets are also being used as a debris-free source for X-ray microscopy studies[13]. Elongated laser-produced plasmas, e.g. from carbon, are being employed in preliminary X-ray laser studies with the new terawatt laser.

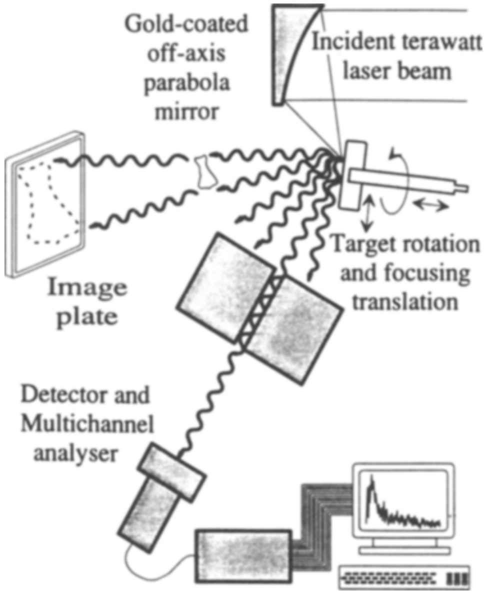


Fig. 6. Generation of a micro-plasma for X-ray imaging (left)

Fig. 7. X-ray image of a human finger bone and a paper clip imbedded in 1.5 cm of soft tissue (top)

APPLICATIONS OF WHITE-LIGHT FEMTOSECOND PULSES

By focussing high-power radiation in water, self-phase modulation leads to intense generation of white light, that can be used for many types of temporally resolved experiments. A pump/probe set up is presently being used for ultra-fast chemistry studies. If a temporal resolution compatible with a streak camera (~1ps) is adequate, such an instrument can be used for simultaneous recording of the temporal response for a distribution of wavelengths, dispersing the light spectrally along the entrance slit of the camera, which is equipped with a 2D ccd detector. Such a system, illustrated in Fig. 8, can be used for photon migration studies in tissue. The white light spectrum, with enhanced intensity towards the primary laser radiation at 792 nm, is shown spectrally corrected in Fig. 9. Tissue transillumination experiments allow multi-spectral determination of tissue optical constants and light fluxes, with application to optical mammography, photodynamic tumour therapy and brain oxygenation measurements. Data for transmillumination of a human finger are shown in Fig. 10[14]. The final slope of the logarithm of the temporal dispersion curves is proportional to the tissue absorption coefficient and reflects the decreasing haemoglobine absorption for longer wavelengths. In other experiments optical properties of green leaves and paper sheets are being studied in time-resolved multiple scattering experiments.

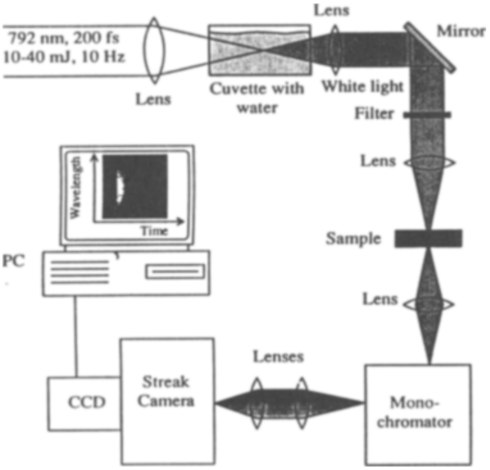


Fig. 8. Set-up for picosecond experiments with white light.

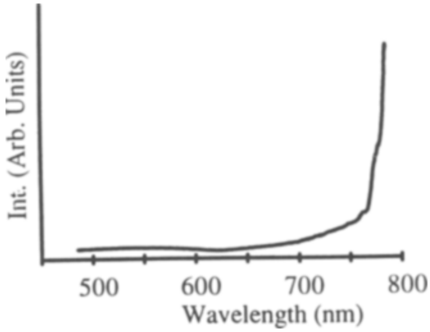


Fig. 9. Spectrum of white light generated through self-phase mondulation.

DISCUSSION

As illustrated in the present paper, the easy access to ultra-high intensity laser light through chirped-pulse amplification in table-top laser systems enables a whole host of experiments that otherwise would be very hard to perform. Powers beyond the 1 TW level may become accessible either through the use of LISAF or LICAF final amplification stages, that can be efficiently flashlamp-pumped (excited state lifetime ~60 μs), or through the use of even higher-energy, high-repetition rate Nd:YAG lasers for pumping large Ti:S crystals (upper state lifetime ~3 μs). The tunability of such systems, already demonstrated in our present set-up, is of particular interest in connection with high harmonic generation, since it gives access to tunable coherent soft X-ray radiation.

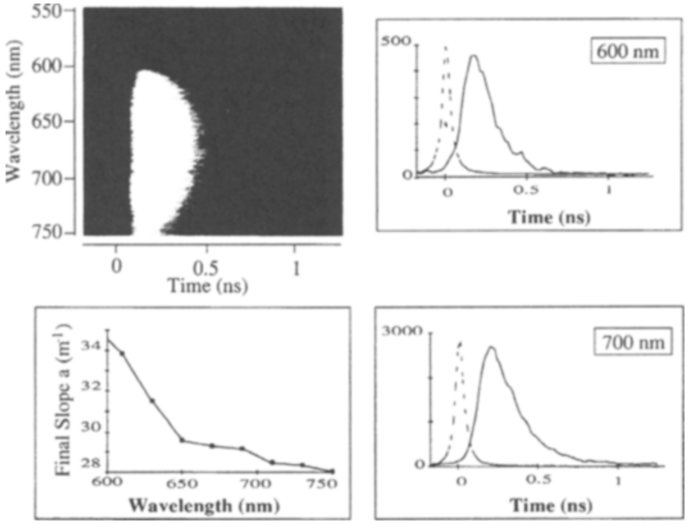


Fig. 10. Multi-spectral streak-camera recording of the light emerging through a human finger. Intensity profiles and a plot of the final slope of the intensity logarithm are given.

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