Electron Generation and Transport using Second Harmonic Laser Pulses for Fast Ignition Laser Fusion Energy

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PORTABLE HYDROCARBON SENSOR FOR ENVIRONMENTAL APPLICATIONS

The quality of the environment is an increasing concern for the population. Since environmental monitoring is a complex domain and must be optimized for each species which needs to be measured, a chemical approach is the more commonly used approach; but it requires time and laboratory measurements for many applications. This is the case for detecting the presence of hydrocarbons in water and, therefore, a team of researchers from University of Alberta has developed a new rapid, low-cost portable sensor based on fluorescence. Fluorescence is created by an ultraviolet LED and is detected by a CCD spectrometer followed by the analysis of the signal spectrum. They have successfully tested their system on oil-sands process affected water and diesel contaminated soils, and the results demonstrated that they can detect hydrocarbons at the parts-per-million level. They have identified system improvements, and a low-cost hand-held instrument should become available in the near future.

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NOUVEAU CAPTEUR PORTATIF POUR LES HYDROCARBURES ET AUTRES APPLICATIONS ENVIRONNEMENTALES

La qualité de l'environnement est une préoccupation croissante pour la population. Étant donné que la surveillance de l'environnement est un domaine complexe, qui doit être adaptée selon les polluants à mesurer, c'est l'approche chimique qui est la plus couramment utilisée. Cependant, cette approche requiert du temps et plusieurs mesures en laboratoire pour de nombreuses applications. C'est le cas notamment pour détecter la présence d'hydrocarbures dans l'eau. Ainsi, une équipe de chercheurs de l'Université de l'Alberta a mis au point un nouveau capteur portatif, rapide et à faible coût basé sur la fluorescence. La fluorescence est créée par une DEL ultraviolet et est détectée à l'aide d'un spectromètre CCD. L'analyse du spectre du signal détermine le taux de polluant. Les chercheurs ont testé avec succès leur système sur l'eau affectée par les procédés d'extraction de l'huile des sables bitumineux et des sols contaminés par le diesel et ils ont démontré qu'ils peuvent détecter les hydrocarbures au niveau de parties par million. Ils ont ainsi identifié les améliorations requises afin de finaliser le développement d'un instrument portatif à faible coût qui deviendra disponible dans un avenir proche.

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ELECTRON GENERATION AND TRANSPORT USING SECOND HARMONIC LASER PULSES FOR FAST IGNITION LASER FUSION ENERGY

Fusion energy holds the promise of a source of clean, almost inexhaustible, green house gas free, and low radioactive waste energy for mankind. The quest to develop fusion energy has been the goal of a large group of scientists and engineers around the world for the past five decades, and they are finally approaching the threshold of success. In particular, a full proof of principle experiment demonstrating large energy yield from laser fusion is expected from the huge mega-joule laser in the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in USA within the next year. With the rapid advancement of lasers it also now appears feasible to build the robust and efficient laser drivers required for such systems. In fact, new proposals are already on the drawing board to develop more efficient and lower power routes to laser fusion energy, including one that uses a separate ultrashort laser to actually ignite the fusion reactions in the compressed fuel. Such a system would use much lower energy, several hundred kilojoules, and laser pulses to actually compress the fuel. This technique, called fast ignition, requires an intermediary species such as megavolt energy electrons to actually carry the energy the last 100 microns from the point where the ultrashort laser light is absorbed to the compressed fuel core itself. The investigation led by the University of Alberta group, headed by Prof. Fedosejevs and in collaboration with an international team of scientists, report on the characteristics of an ultrashort second harmonic laser light pulse for such a driver. This shorter wavelength driver could potentially produce a more optimum electron energy spectrum for better coupling to the ignition spot on the compressed core. The experiments themselves were carried out in the TITAN petawatt laser laboratory located nearby the NIF facility at LLNL, and the measured electron characteristics appear promising for the use of such second harmonic wavelength drivers in future fast ignition systems.

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GÉNÉRATION ET TRANSPORT D'ÉLECTRONS PAR LASER POUR DÉCLENCHER LA FUSION

L'énergie de fusion promet d'être pour l'humanité une source d'énergie propre, presque inépuisable, libre de gaz à effet de serre et faible en déchets radioactifs. Développer l'énergie de fusion a été la quête d'un grand nombre de groupes scientifiques du monde entier au cours des cinq dernières décennies, et ils approchent enfin du seuil de réussite. En particulier, la preuve complète du rendement énergétique de la fusion par laser par une expérience déterminante est prévue en utilisant le laser mégajoule du National Ignition Facility (NIF) au Lawrence Livermore National Laboratory (LLNL) aux États-Unis dès l'année prochaine. Avec l'avancement rapide des lasers, il semble désormais possible de construire des lasers robustes et efficaces nécessaires pour de tels systèmes. En fait, les nouvelles propositions sont déjà sur la planche à dessin pour développer des solutions plus efficaces et à plus faible puissance pour la fusion par laser, dont une qui utilise un laser à ondes ultracourtes pour provoquer les réactions de fusion dans le combustible compressé. Un tel système utiliserait des pulsations lasers avec une énergie beaucoup plus basse, soit plusieurs centaines de kilojoules, pour compresser le carburant. Cette technique, appelée allumage rapide, exige une espèce intermédiaire tels des électrons d'énergie mégavolt pour porter l'énergie dans les derniers 100 microns entre le point où la lumière laser ultracourte est absorbée et le cœur du carburant comprimé. La recherche menée par le groupe de l'Université de l'Alberta, dirigé par le Professeur Fedosejevs en collaboration avec une équipe internationale de scientifiques, porte sur l'étude des caractéristiques d'un laser ultra-court de seconde harmonique pour initier ce phénomène. Ce pilote de longueur d'onde plus courte pourrait potentiellement produire un spectre d'énergie électronique plus optimal pour un meilleur couplage d'allumage sur le noyau compressé. Les expériences ont été effectuées avec le laser petawatt TITAN situé à proximité de l'installation de NIF à LLNL et les caractéristiques des électrons mesurées semblent prometteuses pour l'utilisation de ces pilotes de seconde harmonique dans les futurs systèmes d'allumage rapide.

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Electron Generation and Transport using Second Harmonic Laser Pulses for Fast Ignition Laser Fusion Energy

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ABSTRACT – A team of University of Alberta researchers, in collaboration with an international team of investigators, has spearheaded an experiment to study the generation and transport of MeV electrons produced by ultra-high intensity second harmonic Nd:Glass laser pulses. Intensities of up to 5×10^{19} W cm^{-2} have been used to irradiate a variety of targets to investigate the conversion efficiency into MeV energy electrons, as well as the energy spectrum and angular divergence of such electrons. Their transport through a cone tip simulating the generation of an energetic electron beam for the fast ignition of a laser-compressed fuel core was also measured. The experiments were carried out at the Titan high intensity laser facility located at the Lawrence Livermore National Laboratory. The experiment is the first step towards evaluating the potential effectiveness of using prepulse-free shorter wavelength second harmonic laser pulses as ignition sources for Fast Ignition Fusion Energy.

1. INTRODUCTION

Fusion energy is the ultimate energy source available to mankind in order to convert to a greenhouse gas free energy economy. It is the same source that energizes our sun and the stars and, thus, is the initial source of most of the energy sources used today such as solar, wind and fossil fuels. However, learning how to tame and control fusion energy on earth has proven to be a very challenging task, given the very high temperatures (100,000,000 C) that are required. Two routes are currently pursued as mainline approaches, one being magnetic confinement fusion using low densities and long confinement times as embodied in the leading international project, ITER[1], and the second being inertial confinement fusion using very high compressed densities and very rapid reaction times as embodied in the leading USA program, NIF[2]. Both projects are designed to demonstrate for the first time a net gain of the order of 10 to 20 times in terms of fusion energy yield versus energy invested in heating the deuterium and tritium fuel. However, the laser approach is expected to demonstrate this result within the next year or so while the magnetic approach, which is in its initial construction phase, will take ten to fifteen years to achieve this goal. At the same time the technology for building the required high efficiency, high repetition rate, multi 100kJ to megajoule class laser systems is developing rapidly.

The mainline laser fusion approach currently uses 100 TW, 10 ns shaped laser pulses both to heat and compress the fuel to a high density and high temperature core which self ignites and starts a self sustaining fusion burn wave through the fuel[3]. Such a technique requires megajoule scale laser energies. However, newer approaches are already being explored such as fast ignition[4] which has been described in a previous PHOTONS article[5], and shock ignition[6] which could reduce the required laser energy by a factor of about five times and lead to higher efficiency fuel burn. The promising prospects of these new approaches have stimulated a new European collaborative project called HiPER, which is currently in the design study phase, to build a test demonstration reactor using one of these two approaches.

The laser-plasma group at the University of Alberta has a long history of laser fusion related studies from early CO_2 laser heated plasma studies to short wavelength KrF laser driven plasma hydrodynamic and laser interaction studies. Recently the group has initiated a new collaboration with the Lawrence Livermore National Laboratory (LLNL) and a number of University and Industrial partners to study the physics of the Fast Ignition approach at the TITAN petawatt laser facility at LLNL. In the past year the University of Alberta group proposed and led the first investigations using the second harmonic wavelength (527nm) of the Nd:Glass laser pulses at the TITAN facility. We present here an overview of that experiment and a few preliminary results.

2. SECOND HARMONIC GENERATION

The TITAN Laser facility at LLNL is a chirped pulse amplification (CPA) laser capable of generating 200J 500fs laser pulses at the fundamental wavelength of 1054 nm of the Nd:Phosphate glass disk amplifiers used. The intrinsic amplified spontaneous emission leads to a small prepulse of the order of 1 to 10 mJ lasting approximately 2 ns prior to the main pulse. Such a prepulse when focused down to the 10 micron scale interaction spot is sufficient to create preplasma on the target surface extending 10's of microns on front of the solid surface. This preplasma significantly alters the interaction of the main pulse with the surface, modifying the temperature and angular distribution of the MeV electrons and ions generated in the interaction. These electrons or ions are the primary mechanism to couple energy from the laser into the ignition hot spot on the compressed target core. One way to avoid such a prepulse is to convert the laser light into its second harmonic using a thin KDP frequency doubling crystal. Because the conversion efficiency is proportional to intensity, the very low intensity prepulse becomes negligible compared to the main pulse. In addition, the electron temperature, which is proportional to $(I\lambda^2)^q$ where q is in the range of 1/3 to 1/2, I is the intensity and λ the wavelength, will become colder and potentially could be better matched to heating and igniting the compressed fuel core. In order to explore the interaction under prepulse free conditions and lower temperature electron production, the University of Alberta group proposed carrying out an experiment at the second harmonic wavelength.

These experiments represented the first time that the 700fs pulses at the TITAN laser facility were converted to the second harmonic wavelength. This necessitated the insertion of a 20 cm diameter 2mm thick frequency doubling crystal and replacement of large aperture beam steering mirrors in the vacuum compressor chamber and target chamber. A dielectric coated f/3 off-axis parabola was used to focus the light to a spot size of about 7μm in the vacuum target chamber. The University of Alberta group designed and built autocorrelator and prepulse monitor diagnostic systems for characterizing the second harmonic pulses. The LLNL group and researchers from the Ohio State University provided FROG pulse characterization systems for both the incident and reflected laser pulses from the target and the LLNL group and UCSD researchers provided focal spot measurement diagnostic systems. Because of the limited 20 cm diameter of the available frequency doubling crystal the 25cm beam was apodized to an 18cm diameter beam and thus only about half the full beam energy could be used for the experiment. Pulse energies of 50J in 700fs could be obtained at conversion efficiencies of up to 60% into the 527nm pulses. When focused on target the peak intensities obtained were 5×10^{19} W cm^{-2}. As expected, the prepulse levels were less than the measurement limit of the prepulse diagnostic, which was 10 microjoules. Thus the preplasma formation was at least two to three orders of magnitude reduced from the equivalent 1 micron experiments. A typical focal spot measured at low intensity together with the equivalent intensity distribution function for the high intensity shots is shown in Fig. 1. Some residual astigmatism is observed in the beam which may be due to small distortions in the large compressor gratings. This represents some of the highest intensity second harmonic pulses focused on target in the world.

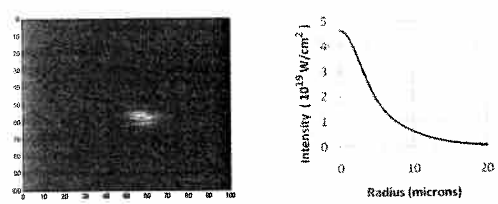

Figure 1: Target focal spot at low intensity (100 x 100 micron region shown) and the radially symmetrized equivalent intensity distribution at high intensity.

3. ELECTRON MEASUREMENTS

Several different target geometries were used in the experiments, as shown in Fig. 2. The simplest were planar aluminum foils with 25 micron thick copper layers buried at various depths. The copper layers were used to diagnose the absolute number and angular divergence of the MeV electrons generated in the forward direction through the foil target by observing the integrated and spatially resolved K_α x-ray line emission at 8048 eV photon energy from the copper layer at various buried depths. The second type of target was a solid aluminum cone with a 30 μm diameter tip opening covered with a similar layered foil target. The laser pulse is fired into the tip of the cone and the electron transport again measured. This geometry is chosen to simulate the case of using a cone guide to direct the light into an imploding fuel capsule, a geometry first demonstrated by the group in Japan[8]. The final target geometry was an aluminum cone with a copper wire attached to the tip to look at the transport of the electrons through the cone tip and along the high density wire to emulate the high density plasma region outside of the compressed core. All these targets were fabricated by General Atomics for the experiments.

Both curved crystal Bragg reflection mirrors and a grazing incidence Kirkpatrick-Baez (KB) x-ray microscope were used to image the copper K_α emission. An example of such emission is shown in Fig. 3 from the Bragg imager for the case of a cone-wire target. One can see both the copper K_α emission from the MeV electrons travelling along the wire and a faint image of the Bremsstrahlung emission from the laser absorption spot in the cone. Using the layered foil targets and by taking a series of measurements at various buried layer depths the divergence of the electron beam through the target can be measured. In order to compare the results to the case where a preplasma is present an artificially induced prepulse was generated in the laser system. This required a 10 J, 2 ns prepulse at the fundamental wavelength of 1054 nm in order to generate a small 3mJ prepulse at 527 nm due to the relatively low conversion efficiency in the large aperture second harmonic crystal for nanosecond pulses. The K_α emission measurements were repeated with this prepulse. Preliminary measurements of the spot diameters versus layer depth obtained from KB imaging diagnostic are plotted in Fig. 4. It can be seen that the electron beam spot size observed for the K_α emission spot is slightly smaller for the case of no prepulse compared to that with prepulse. Measurements for the solid aluminum cone targets indicate slightly larger divergence angles for the K_α emission spots for both cases indicative of the additional effect of the cone aperture on electron transport. The actual determination of the electron beam divergence requires numerical modeling of the electron source distribution and propagation through the target including self induced magnetic and electric space charge fields. This detailed analysis is currently under way.

Another important characteristic of the electron generation process is the effective temperature of the

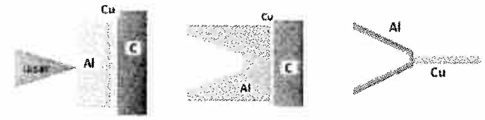

Figure 2: *Diagrams of the three target types used in the experiments.*

Figure 3: *Image of a cone wire target taken with a Bragg crystal imaging mirror. The laser enters from the lower left corner). A tiny emission spot from the laser absorption region is visible and then the extended copper k-alpha emission along the length of the wire is observed.*

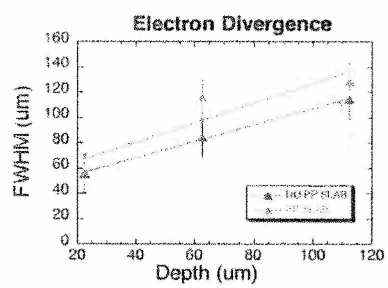

Figure 4: *Cu K_α spot diameter measured with the KB microscope versus depth of the Cu layer for planar targets.*

electron distribution function produced. This is measured in the experiments both at 15 degrees and 25 degrees off axis by two magnetic electron spectrometers. A typical electron spectrum for a solid target is shown in Fig. 5 indicating an escaping electron temperature of 1.1 MeV at 25°. A strong angular dependence of the electron energy distribution was found with colder measured electron temperatures at 25 degrees off axis versus 15 degrees off axis. This is in agreement with previously observed higher energy electron emission on axis. The measured temperatures are significantly colder than similar temperatures measured in 1054 nm experiments on the same facility. The angular peaking of the electron emission also leads to an angular peaking of the Bremsstrahlung emission for these relativistic energies. Another set of measurements characterized the angularly and spectrally resolved x-ray emission using a series of filtered detectors at different angles off axis in the forward direction. Once deconvolved, these yield a complementary set of measurements of electron divergence and energy distribution function. These results are currently being analyzed to compare to the K_α emission spot divergence measurements.

4. CONCLUSION

The present experiments are some of the first to systematically study the electron generation and transport from second harmonic laser pulse at ultrahigh intensities. The preliminary analysis of the results indicate electron divergences not too different than previously reported for 1 micron interactions. Electron temperatures are colder than for the 1 micron case and indicate the potential advantage of using green laser pulses to generate high current fluxes at optimum electron energies for heating the fast ignition spot. All of the results are being further analyzed and compared to extensive 2D and 3D numerical modeling.

A picture of the experimental team is shown in Fig. 6. Overall, the experiments have led to a detailed characterization of the electron generation and were an excellent opportunity for students to obtain training on a world leading laser facility.

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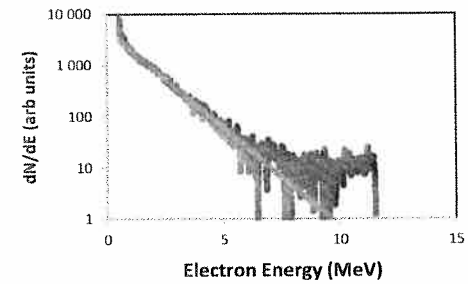

Figure 5: *Typical electron spectrometer signal at 25 degrees off axis. A line fit is shown for a 1.1 MeV temperature distribution.*

Figure 6: *The target experiment team.*

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