Thursday, September 12, 2013

OP.Th_A1

The Laser Mega-Joule : LMJ & PETAL status and Program Overview

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The laser Megajoule (LMJ), developed by the French *Commissariat à l'Energie Atomique et aux Energies Alternatives* (CEA), will be a cornerstone of the French Simulation Program, which combines improvement of physics models, high performance numerical simulation, and experimental validation.
The LMJ facility is under construction at CEA CESTA and will provide the experimental capabilities to study High-Energy Density Physics (HEDP). One of its goals is to obtain ignition and burn of DT-filled capsules imploded, through indirect drive scheme, inside rugby-shape hohlraum.
The PETAL project consists in the addition of one short-pulse (ps) ultra-high-power, high-energy beam (kJ) to the LMJ facility. PETAL will offer a combination of a very high intensity multi-petawatt beam, synchronized with the nanosecond beams of the LMJ. This combination will expand the LMJ experimental field on HEDP.
This paper presents an update of LMJ & PETAL status, together with the development of the overall program including targets, plasma diagnostics and simulation tools.

Figure 1: One of the four LMJ laser bays with 7 LMJ bundles (56 beams) and PETAL beam

OP.Th_A2

The updated advancements of inertial confinement fusion program in China

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The goal for the inertial confinement (ICF) program in China is to achieve ignition and plasma burning in laboratory in 2020 through Shengguang (SG) series.

Since 2000, the precise physics experiments conducted on SG-II and SG-III prototype laser facilities with laser energy of 3-10kJ have attained many important achievements to better understand the implosion dynamics and radiation generation and transport. The further target physics research will perform on SG-III laser facility (48 beams, total laser energy of about 200 kJ, blue light, 3-5ns)) in 2013, and full energy in 2014.

A new hybrid indirect-direct drive ignition scheme for inertial confinement fusion is proposed. A steady high density plateau newly formed between the radiation and electron ablation fronts suppresses the rarefaction at the radiation ablation front and greatly enhances the drive pressure and the imploding velocity. The latter drives an enhanced shock-compression wave to stop the multiple shock- reflections at the main fuel/hot spot, and thus to prevent the server hydrodynamic instability. Meanwhile, the rapid ignition and burn are realized. Numerical simulations show that an energy yield of 17.4MJ and an energy gain of 13 are achieved. The experiments for some physical processes of the hybrid-drive scheme will be conducted on SG-III this summer.

Fast ignition is one of important goals addition to central hot spot ignition in China. SG-IIU and PW laser facilities are coupled to investigate the hot spot formation for fast ignition. In recent years, a great number of experiments and numerical simulations have obtained many important results, involving target designs, hot electron transport and collimation by spontaneous and imposed magnetic fields in overdense plasmas.

The first data from the Orion laser; measurements of the spectrum from hot dense plasma

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The newly commissioned Orion laser system has been used to study dense plasmas created by a combination of short pulse laser heating and compression by laser driven shock, using the nanosecond and sub-picosecond laser beams available at the facility. The plasma density was systematically varied between 1 g/cc and 10 g/cc by using aluminium samples buried in plastic or diamond sheets. The aluminium was heated to electron temperatures between 500 eV and 700 eV allowing the plasma conditions to be diagnosed by emission spectroscopy of the aluminium K-shell. These were inferred from comparison with a variety of codes, including FLY and FLYCHK spectra and from radiation-hydrodynamic simulations.

The time-resolved aluminium X-ray emission was recorded using a spectrometer coupled to an ultrafast X-ray streak camera, with additional time-integrated spectrometers recording onto image plate. By using different materials to tamp the aluminium and shock compression to alter the sample density, a systematic study of the change in the aluminium spectrum with density was carried out. The K-shell spectra show evidence of the lowering of the ionization potential, where the data are in reasonable agreement with FLY and FLYCHK when using the standard treatment of ionization potential depression proposed by Stewart and Pyatt. The data have also been compared to more sophisticated models and the results are presented.

OP.Th_A4

OVERVIEW OF THE HIGH ENERGY DENSITY SCIENCE PROGRAM ON THE Z FACILITY AT SANDIA NATIONAL LABORATORIES

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The refurbished Z facility can efficiently create currents as large as 26 Million Amperes. These large currents create large magnetic fields that, in turn, create very large pressures in conducting materials. These very large pressures have been used to create unique conditions for high energy density science experiments. Historically, a focus of Z-pinch research has been in the area of radiation generation through the use of cylindrical implosions of arrays of wires or puffs of gas. We have recently reconstituted the capability to perform gas puff experiments on the Z facility and achieved record x-ray yields from puffs of Argon gas. We have also continued to advance our study of radiation-dominated plasmas using the output from these very energetic x-ray sources.

The very large magnetic pressure has also been used to create uniform, high velocity flyer plates and impact them in to materials of interest to determine both the Hugoniot response of the material and, most recently, to study the temperature of the material under shock compression. The ability to carefully control the rate of change of the magnetic field by changing the machine configuration enables exploration of material properties at high pressures off of the Hugoniot, including both shockless and most recently shock-ramp compression. In the area of shockless compression, pressures obtainable are limited in planar geometries. By performing shockless compression experiments in cylindrical geometry much higher pressures can be obtained, but diagnosing the materials is much more challenging. Recently experiments have been performed demonstrating a new approach to measuring dynamic material properties in converging geometries.

In the area of inertial confinement fusion, progress continues to be made on the Magnetized Liner Inertial Fusion concept. This concept relies on a cylindrically imploding liner, an axial magnetic field, and a laser heated fuel region to significantly relax the requirements for achieving significant fusion yield on the Z facility. Initial experiments assessing the growth of the Magneto-Rayleigh Taylor instability in the presence of an axial magnetic field are promising.

*Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

O.Th_A5

High-intensity laser-plasma interaction physics for advanced ICF ignition schemes

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We have explored laser-plasma couplings in different irradiation and plasma conditions. The experiments have been conducted with the LULI2000 installation with both long (nanosecond) and short (picosecond) pulses. The propagation and energy deposition of a high-intensity laser beam in well-defined preformed plasmas have been studied using a large set of diagnostics. Understanding laser-plasma interaction physics is essential for many applications, in particular laser fusion. New laser fusion schemes based on additional short igniting pulses look very promising. Nevertheless, their efficiency depends first on the controlled propagation and efficient coupling between high-intensity laser pulses and the plasma corona of a fusion target. These interaction conditions correspond to higher intensities than most of the previous studies done over the years in this field, which means above the thresholds of most of the parametric instabilities. The behavior of non-linear mechanisms is very difficult to predict with numerical simulations and the role of well-controlled experiments is essential.

The high energy delivered by the LULI2000 laser was used to produce large and hot plasmas that are needed to emulate the plasma conditions of fusion experiments. Low-density foams and thin exploded foils were used to preform millimeter size plasmas with electron temperature in the keV range. The interaction beam was the Pico2000 laser beam with a pulse duration of 1-5ps and intensities up to $6\text{x}10^{18}$ W/cm^2 at 0.53 μm. A random phase plate to control the intensity distribution inside the focal volume was used to study laser-plasma interaction physics issues in the context of shock ignition. Intensities between $3\text{x}10^{15}$ and $3\text{x}10^{16}$ W/cm^2 in plasmas of various electronic densities (from 3% to critical density) have been used to measure filamentation, self-focusing, absorption, stimulated Brillouin and Raman scattering. Relativistic transparency and hole boring were studied with new imaging diagnostics and accelerated protons spectra in over-critical plasmas which were produced by the ionization of foams with the nanosecond pulse. The picosecond laser beam was used tightly focused with a pulse duration of 1ps, reaching intensities of $3\text{x}10^{18}$ W/cm^2 at 0.53 μm.

Finally, we will discuss interaction physics in more futurist schemes like those based on multiple-fiber lasers or new designs to address advanced fuels.

O.Th_A6

Backscatter Instabilities in Long Scale Length Shock Ignition Plasma Conditions

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Shock ignition is one of the recently proposed [1-3] routes to increasing the efficiency of Inertial Fusion Energy by separating the compression and the ignition phases of the interaction. In this case the compression pulse does not have to be so energetic that it causes self ignition in the central hot spot, thus relaxing the implosion drive energy requirement considerably. The ignition of the fusion reactions is triggered by a rapid intense shock wave converging to the fuel core driven by an intense laser spike at the end of the compression pulse. Various laser pulse shapes and intensities have been proposed for this intense shock driving pulse but it is clear that the interaction will require intensities of several times 10^{15} W cm^{-2} up to 10^{16} W cm^{-2} at which a number of laser plasma instabilities such as Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS) and Two Plasmon Decay (TPD) instabilities will be driven very strongly. These instabilities can lead to backscatter of a significant fraction of the incident laser light and generation of hot electrons which may interfere with the compression of the target core.

In order to study these processes, measurements have been carried out at the Titan laser facility at the Lawrence Livermore National Laboratory to study the interaction of short 1 to 20 ps 527 nm pulses with a hot, large scale length plasma created by a 500 J, 5 ns laser pulse at 1054 nm onto planar targets. The ultrashort pulse was focused into the long scale length plasma generated by the nanosecond pulse. The backscattered radiation was measured using both time integrated measurements and spectrally resolved streak camera measurements. Hot electron heating was measured by observing the direct x-ray emission from the target and the k-alpha emission from buried copper tracer layers. Preliminary analysis of the results indicates significant levels of SBS and SRS backscatter on the order of 10% to 20% of the incident radiation in this strongly driven regime. The results will be presented and discussed.

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O.Th_A7

Structural stability analysis of the ultra-intense laser/plasma interaction: explaining multiple results for the same simulations and experiments

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The current understanding of laser/plasma interaction implicitly assumes a plasma dynamics just depending on the physical parameters, like the laser intensity I_0, the plasma density n_0 and the angle of incidence. This work demonstrates the importance of the initial conditions and it explains the contradictory laser energy absorption given by experiments and particle-in-cell (PIC) simulations (see Table 1.1 in Ref. [2]). Following a recent laser/plasma interaction semi-analytical model [1], extended for oblique incidence, a detailed analysis of its structural stability dynamics, varying I_0 and n_0 is carried out. The model exhibits several kinds of stable attractors of the plasma dynamics with important physical consequences. One of the attractors, occurring for large enough I_0, is a stable periodic solution where the electron plasma boundary (EPB) oscillates around the ion density interface with the laser frequency. In this case, the maximum distance explored by the EPB into the vacuum, $d_{\max}$, is a strong non monotonic function of I_0 for oblique incidence; i.e. very disparate $d_{\max}$ values for very close laser intensities, and hence very different absorptions. On the other hand, for I_0 below certain threshold, several stable periodic, multi-periodic and chaotic attractors with very disparate values of both $d_{\max}$ and laser absorption energy coexist. Since some of these stable solutions occur for exactly the same value of the physical parameters, the initial conditions (pulse history amongst other factors) are crucial because they will determine the attractor to which the plasma will evolve. This result, corroborated by PIC calculations, gives a new perspective to explain old contradictory experiments and simulations. The consequences to the design of future experiments are discussed.

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O.Th_A8

The Role of Fast-Electron-Driven Wake-Fields in the Heating of Solid Targets Irradiated by Intense Lasers

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It is currently believed that solid density targets irradiated by relativistically-intense lasers heat as a result of a collisional return current, and this forms the basis of the “hybrid” approach to modeling such interactions. We will present evidence that in the heating mechanism is enhanced by the collisional damping of large-amplitude plasma waves induced by the fast electron bunches. As a result, solid targets heat at a greater rate than previously predicted. This mechanism is different to the well known single particle energy loss mechanism due to the induction of plasma waves.

The work involves high resolution, collisional particle-in-cell modeling. We are working on an alternative “hybrid” technique that allows this effect to be modeled with reduced computational overhead.

O.Th_B1

Novel attosecond pulses based on relativistic electron sheets

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We propose a novel double-layer scheme [1] to generate a uniform relativistic electron sheet (RES). The generated RES is free of transverse motion, which can dramatically degrade the Doppler shift factor for coherent Thomson scattering (CTS) from $4\gamma^2$ to its square root 2γ. The key of the scheme is that the second thicker foil (reflector) completely blocks the laser and the reflected light interacts with RES again to cancel the transverse momentum. Then, RES passes through the reflector with negligible collision loss and freely cruises for a long distance with the fixed γ. Doppler shift factor remains as $4\gamma^2$ during CTS. Finally a quasi-monochromatic as XUV/x-ray pulse is produced.

Recently, we find that, if laser is obliquely incident onto this double-layer target, a giant half-cycle XUV/x-ray (HCX) pulse can be generated [2]. For the oblique incidence, the reflected light kicks RES and gives it a transverse momentum, which is simply about $\tan\theta$ (normalized to mc), θ is incident angle. The transverse current of RES emits HCX, which co-moves with RES, gets amplified and finally reaches saturation. A TW/24as HCX generation is shown in 2D-PIC simulations. The simple analytical model is also developed and explains the simulation well. It should be stressed that this is the very first time that XUV/x-ray sources goes to half-cycle regime. HCX will open new era of XUV/x-ray optics and attosecond science.

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O.Th_B2

Precision Measurement of Delbrück Scattering via Laser Compton Scattered γ-rays

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Precision measurements such as the muon anomalous magnetic moment have indicated deviations from the standard model [1] and have in turn prompted higher precision theoretical calculations [2]. Delbrück scattering is the scattering of photons off the Coulomb field of nuclei via virtual electron-positron pairs (Fig. 1) [3] and has been experimentally measured using γ-rays from radioactivities and following neutron capture reactions [4].

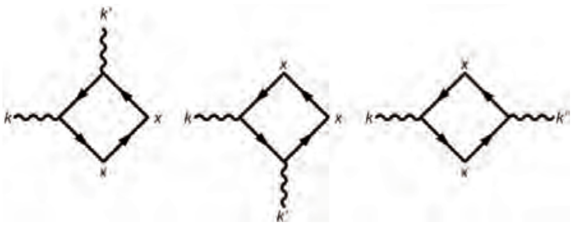

Figure 1: Three of six lowest order Feynman diagrams for Delbrück scattering (3 others with internal electron loop reversed). ***k*** and ***k'*** are incoming and outgoing photons. ***x***'s are the Coulomb field.

However, because low flux γ-rays from nuclear transitions have been used in the low photon energy regime (< 20 MeV) fairly large error bars exist in the data [4]. In addition, due to the complexity and time consuming nature of the theoretical calculation the scattering cross sections are obtained from tables with interpolation between the tabular values [5]. In recent years high flux γ-ray sources via laser Compton scattering (LCS) using energy-recovery linacs have been proposed [6]. These sources allow measuring the Delbrück scattering with high precision. We will present our own independent calculations for the scattering cross section and show what precision can be obtained using the new LCS γ-ray sources in the low photon energy regime.

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O.Th_B3

Strong terahertz generation from relativistic laser-solid interactions

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Terahertz radiation has been attracted much interest due to increasingly wide applications. Though THz radiation can be generated with various ways, it is still a big challenge to obtain strong tabletop sources. Plasmas, with an advantage of no damage limit, are promising medium to generate strong THz radiation. THz radiation from femtosecond laser-induced plasma filaments in low density gases has been reported. However, the radiation is found to be saturated with pump laser energy. Intense laser-solid interactions, in which high laser intensity (up to $10^{19\text{-}20}$W/cm^2) can be applied, are expected to generate stronger THz sources.

We have symmetrically studied strong THz radiation from solid targets driven by relativistic laser pulses. The experiments were carried out using the Xtreme Light II (XL-II) Ti: sapphire femtosecond laser system at the Institute of Physics, Chinese Academy of Sciences, and the COMET sub-picosecond laser system at the Lawrence Livermore National Laboratory, respectively. THz radiation with a pulse energy of tens μJ/sr (driven by femtosecond laser), even ~mJ/sr (driven by sub-picosecond laser) is observed. In this talk, the THz polarization, temporal waveform, angular distribution and energy dependence on the laser energy will be presented. We find that the radiation is dependent on the preplasma density scale length. No saturation effect is observed. We believe that The THz radiation is probably attributed to the self-organized transient fast electron currents formed along the target surface when the plasma density profile is steep, while, the linear mode conversion mechanism when a large preplasma is presented.

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O.Th_B4

Terahertz radiation by two-color lasers with the second laser at an arbitrary harmonic

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The two color laser scheme that applying the fundamental and second-harmonic waves mixed to a gas shows high efficiency for THz radiation generation. However, the highest field strength of the THz radiation obtained from experiments is below 1 MV/cm. Whether even stronger THz radiation can be produced with this scheme is interesting. There are also some inconsistent experimental results to explain, e.g., some experiments show sine dependence of the THz strength on the relative phase difference while others show cosine dependence. Besides, it is required to study whether the two color laser scheme can be extended to use other order harmonic and which order harmonic is more favorable.

We derive a general selection rule concerning the harmonic order of the second laser. The THz radiation can be generated only when the second laser frequency is at an even harmonic. With the second harmonic, the highest efficiency of THz yield can be achieved. We also find that the THz strength is sensitive to the laser carrier envelope (CE) phases and therefore, either sine or cosine dependence of the THz strength on the relative phase difference is possible when different CE phases are taken. Third, we find that the THz strength versus the laser intensity shows a monotonic growth region and followed by a saturation plateau due to complete ionization of gases. Hence, one can obtain stronger THz radiation by choosing such laser intensity at which a gas is just ionized completely. THz radiation of 7 MV/cm can be generated from helium at the laser intensity of 10^{16}W/cm^{-2}.

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O.Th_C1

High-resolution X-ray Spectromicroscopy Diagnostics of Plasma Produced by High Contrast Femtosecond Laser Pulse Irradiation of Submicron Clusters

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The interaction of ultra- short ultra-intense laser pulses with structured targets, such as clusters, exhibits unique features, stemming from the enhanced absorption of the incident laser light compared to solid targets. Due to the increased absorption, these targets are heated significantly, leading to enhanced emission of x-rays in the KeV - MeV range and generation of electrons and multiple charged ions with kinetic energies from tens of keV to tens of MeV.
An overview of recent experimental and theoretical results, obtained by high-intenseultra-short Ti:Sa laser pulse interaction with different submicron clusters media, will be presented. High-resolution K- and L- shell spectra of plasma generated by ultra intense laser irradiation of submicron-sized CO_2, Ar, Kr, Xe clusters have been measured with intensity 10^{17}- 10^{19} W/cm^2 and a pulse duration of 30 -1000 fs. X-ray spectral methods have been proposed to determine the parameters of the plasma formed at the early stages of its evolution. It has been shown that the spectra of hollow ions are the most informative in the first moments of the heating of a cluster, whereas the diagnostics of the late stages can be performed using the conventional lines of multicharged ions. It is found that hot electrons produced by high contrast laser pulses allow the isochoric heating of clusters and shift the ion balance toward the higher charge states, which enhances both the X-ray line yield and the ion kinetic energy. Using high-resolution X-Ray spectromicroscopy methods the acceleration of fast multicharged ions of Oxygen up to the energies of ~ 1 MeV was observed with not so high, less than 10^{17} W/cm^2, laser intensities. This effect could be explained by self- focusing of laser beam inside the cluster media and will be discussed. Possible applications of cluster plasma as a table-top electron/ion/neutron sources for a material damage study or for radiography will be discussed.

This work was supported by the Funding Program for Next Generation World-Leading Researchers (NEXT Program) from the Japan Society for the Promotion of Science (JSPS). Part of the work was supported by Russian Fund for Fundamental Research grant No. 12-02-91169-GFEN-a. The Los Alamos National Laboratory is operated by Los Alamos National Security, LLC for the NNSA of the U.S. DOE under Contract No. DEAC5206NA25396.

O.Th_C2

Exotic Dense-Matter States Pumped by a Relativistic Laser Plasma in the Radiation-Dominated Regime

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K-shell spectra of solid Al excited by petawatt picosecond laser pulses have been investigated at the Vulcan PW facility. Laser pulses of ultrahigh contrast and 160 J of energy on the target allows interaction studies between the laser field and solid state at 10^{20} W/cm^2. Intense X-ray emission of KK hollow atoms (atoms without n = 1 electrons) from thin aluminium foils is observed in optical laser plasma for the first time. Specifically for 1.5 μm thin foil target the hollow atom yield dominates the resonance line emission. It is suggested that the hollow atoms are predominantly excited by the impact of X-ray photons generated by radiation friction to fast electron currents in solid-density plasma due to Thomson scattering and Bremsstrahlung at the transverse plasma fields. Numerical simulations of Al hollow atom spectra executed with ATOMIC code confirm that the impact of keV photons dominates in atom ionization. Our estimates demonstrate that solid density plasma of relativistic optical laser pulses provides the source of a polychromatic keV range X-ray field of 10^{18} W/cm^2 intensity, and allows the study of excited matter in the radiation dominant regime. High-resolution x-ray spectroscopy of hollow atom radiation is promoted as a powerful tool to study the properties of high energy density plasma under the impact from intense X-ray radiation

O.Th_C3

NEW RESULTS ON THE LASER PRODUCED RELATIVISTIC ELECTRON-POSITRON PAIR PLASMA RESEARCH

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Following initial experiments that produced the high-flux jets of positrons with temperatures of MeV using high-intensity laser facilities [1], we have performed a series of experiments exploring unique characteristics of pair jets and plasmas from the energetic short-pulse lasers on the Titan and OMEGA EP [2] as well as the Osaka LFEX [3] and AWE Orion laser facilities. These experiments focused on the topics of understanding the pair production scaling and collimation. The experiments were performed over a large range of laser parameters including the intensity (10^18 – 10^21 Watts/cm^2), contrast (10^6 – 10^9), and energy (100 – 2000 J). We measured the positron beam emittance to be 100 – 500 mm.mrad, comparable to that used in Stanford Linear Collider [2]. The laser contrast was found to have a large effect to the positron yield [3]. The scaling of pair production vs laser energy has been confirmed to be nonlinear when the laser energy is greater than 1000 J [4]. We found significant effect of the laser intensity to the pair production using Orion and OMEGA EP laser. We have started to explore the pair jet collimation using electromagnetic fields. We aim to use the multi-kilojoule, short-pulse laser systems worldwide in combination with more advanced target designs to create the first relativistic high-density pair plasmas in the laboratory - a completely novel system enabling detailed study of some of the most exotic and energetic systems in the universe [5].

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and funded by the LLNL LDRD program.

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O.Th_C4

Intense γ-ray and pair production in laser-driven dense plasmas

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The advent of next-generation 10-PW laser facilities as part of the ELI project opens up new prospects in laser-matter interaction where ultra-relativistic plasma physics is coupled to quantum electrodynamics (QED) processes. Recent numerical studies [1-2] have thus shown that, for laser intensities approaching 10^{23} W/cm^2, the plasma electrons radiate a significant fraction of their oscillation energy as γ-ray photons, which, in turn, may decay into large numbers of electron-positron pairs. These intertwined plasma and QED processes provide new channels for the laser absorption [3], hence leading to drastic changes in the energy balance of the laser-matter system. As a result, most of the standard mechanisms ruling laser-plasma interaction need revisiting.

In order to address this novel interaction regime, the existing particle-in-cell (PIC) codes must be enriched with algorithms describing the dominant QED processes. Following the works of Refs. [1,2], the parallel code CALDER developed at CEA now features a Monte Carlo scheme accounting for the generation of discrete high-energy photons through the Synchrotron / nonlinear Compton processes. This scheme extends to the QED regime the so-called radiation friction force which is valid at lower intensities where the emission of low-energy photons can be assumed continuous [4]. An additional Monte Carlo scheme implemented into CALDER describes the production of electron-positron pairs via the Breit-Wheeler process arising from the interaction of the high-energy photons with the electromagnetic field.

After detailing the aforementioned Monte Carlo numerical schemes, we will illustrate the influence of the related QED processes in a number of scenarios involving (classically) overdense plasmas. Firstly, we will address the sensitivity to QED effects of the ion acceleration from thin solid-density targets. Secondly, we will present a wire-target configuration yielding a collimated, intense gamma-ray beam. Finally, we will show the influence of QED processes upon the laser generation of Weibel-mediated collisionless shocks [5].

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O.Th_A9

The influence of 3D asymmetries upon the thermonuclear yield in ICF capsule implosions on the National Ignition Facility.

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We report on investigations into the effect of asymmetry on thermonuclear yield in ICF implosions on the NIF. Asymmetries at the interface between the hotspot and the cold dense fuel layer are amplified by the Rayleigh-Taylor instability during the deceleration phase. Where multiple low mode asymmetries interact in three dimensions, structures arise containing non-radial components of momentum which are not extinguished at stagnation, so that not all of kinetic energy is dissipated effectively. In addition the dissipation of kinetic energy can be spread out in time so that whilst the hotspot that may be effectively heated by the arrival of the first imploding dense fuel regions to approach the axis, the remaining inertia arrives too late to provide effective confinement and compression of the hotspot. Low mode asymmetries which change the overall shape of the hotspot increase the surface area leading to increased thermal conduction losses and triggering radiation cooling within the periphery of the hotspot. Higher mode asymmetries promote mixing of the cold fuel layer into the hotspot. This essentially acts as an increased rate of ablation of the dense fuel at the hotspot surface, pulling material with low specific enthalpy into the hotpot and lowering the average hotspot temperature. This cold fuel mix is sufficient to quench the burn even without feed-through of the ablator material into the hotspot.

The contributions of such asymmetries to reductions in the yield are examined by applying different forms of perturbation to the full 3D volume of the DT fuel during the coast phase in order to stimulate the growth of Rayleigh-Taylor instabilities during the deceleration phase. Analysis of the simulation data is then compared with a one-dimensional self-similar model of hotspot energy balance in order quantify the separate contributions of different energy loss mechanisms to the overall hotspot temperature and yield.

Synthetic neutron spectra, radiography and soft X-ray images indicate that different forms of perturbation have characteristic diagnostic signatures which can provide clues as to the dominant source of asymmetry in experiments. Large amplitude single sided perturbations, such as a P1 in the fuel thickness are seen to produce strong anisotropies in the Doppler shift applied to the neutron spectra, arising from residual bulk motion at stagnation. A combination of high bandwidth multimode perturbations together with macroscopic asymmetries is found to give the best agreement with experiment.

Preliminary results from 3D radiation hydrodynamics calculations of the entire capsule volume are presented which attempt to predict the structural form of the perturbations at the stagnation phase, based upon initial capsule defects, dust particles, radiation drive asymmetries, etc. which are amplified by Rayleigh-Taylor growth during implosion.

O.Th_A10

A 1D Hot Spot Mix Model for Diagnosing Performance of NIF Ignition Experiments

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We report results of research in which we match key observables, neutron yield, ion temperature, aerial density, for several NIF ignition experiments using spherically symmetric post-shot simulations with mix models. We use a programmable mix model that prescribes a material and energy mix history profile (i.e. material depth to mix as a function of time) at both the fuel-ablator and gas-fuel interfaces. Scanning over many hundreds of possible mix histories, we find specific solutions that simultaneously satisfy these at least these three. This has been done for five different NIF ignition shot experiments.

The nature of the mix solutions we find indicates that the performance degradation of ignition shots on the NIF is primarily due to fingers of cold DT fuel penetrating deeply into the hot spot. Also, a Richtmyer-Meshkov instability induced component of mixing at the fuel-ablator interface is implied. We will discuss how this work points us toward ways to improve our ability to directly simulate these capsule implosions as well as ways of improving the performance of these capsules on the NIF.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Liver- more National Laboratory under Contract DE-AC52-07NA27344.

O.Th_A11

Kinetic and Multi-Species Effects Relevant to Hot Spot Ignition*

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The use of multidimensional radiation hydrodynamics codes to study laser-based Inertial Confinement Fusion and High Energy Density Physics is ubiquitous. In general, an average-atom single species fluid approximation with no E or B fields is adequate during most of the interaction. However, there are critical times when electric fields, magnetic fields, and multi-fluid/kinetic effects are non-negligible and must be included for proper treatment of the problem[1]. Here we present a number of examples where these effects are included in simulations, and then compare the results with those from standard rad-hydro codes. We employ the hybrid simulation code LSP[2]. Some examples to be presented are the effects of the tail of the electron and ion energy distributions on the formation and burn phases of hot spot ignition[3] and details of the plasma shock as it transits the gas in the core of an ICF capsule[4]. The influence of electric and magnetic fields in 2-D on shocks crossing interfaces will also be discussed.

* Work performed under the auspices of LLNS, LLC under Contract DE-AC52-07NA27344.

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O.Th_A12

The theory and simulation of discrete, large-angle Coulomb collisions

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Many important parameters of plasmas depend explicitly on the value of the Coulomb logarithm, which is in some sense a measure of the importance of multiple, small-angle collisions relative to discrete, binary 'large-angle' collisions. It is well-known that the relative importance of the large-angle events is roughly proportional to $1/\ln\Lambda$, and so they are mostly ignored [1].

However, the moderately coupled regime $2<\ln\Lambda<5$, where large-angle collisions are important, includes inertial confinement fusion and short-pulse laser interactions [2]. In these regimes, large-angle collisions are relatively infrequent but can have noticeable effects because they transfer large amounts of energy or momentum in a single collision. This will affect all properties that depend on the Coulomb logarithm, the shape of the distribution function and, consequently, the rate of fusion reactions. Many papers have predicted effects due to large-angle Coulomb collisions [3][4][5][6], and there is experimental evidence that they cause distortions of ion distribution functions [7].

Most theories of plasmas, including both fluid and Vlasov-Fokker-Planck approaches, depend upon approximations which are not true for large-angle collisions. Other models rely on an arbitrary cut-off or only consider one 'generation' of athermal particles created by discrete collisions. We present a theory that includes both small- and large-angle collisions, and switches between them using a cut-off based on a physical argument. The theory could also be extended to include the effects of nuclear elastic scattering. This theory is incorporated into Monte Carlo simulations of problems relevant to inertial confinement fusion, particularly reactivity and alpha particle stopping and heating.

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O.Th_B5

Laboratory astrophysical experiments using Gekko XII laser system

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Thanks to the development of high-power lasers, it is possible to simulate astrophysical phenomena, such as collisionless shocks, plasma jets, and magnetic filed generation/amplification, in laboratories. In addition to local observations of spaces plasmas by spacecraft and global emission measurements of astrophysical plasmas, a laboratory experiment can be an alternative approach to study space/astrophysical plasma phenomena [1].

In this paper we investigate laboratory experiments to study electrostatic collisionless shock generation [2] and magnetic field amplification via Richtmyer-Meshkov instability using Gekko XII HIPER laser system (352 nm (3ω), 500 ps, ~120 J/beam, one to four beams, $<10^{15}$ W/cm^2) and other large-scale laser systems. Plasmas and shocks were diagnosed transverse to the main laser propagation direction; shadowgraphy, interferometry, and visible self-emission measurements with ICCD and streak cameras. Collective Thomson scattering ion-component measurements were conducted using a probe laser (532 nm, <0.3 J), and electron density, electron and ion temperatures, flow velocity, and Mach number were determined, at the upstream and downstream regions of a shock. We also investigate an experimental proposal to demonstrate the formation of Weibel-instability mediated collisionless shocks using the National Ignition Facility.

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O.Th_B6

Measurement of electrostatic field associated with a shock formed in laser-produced counter-streaming plasmas

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Shock waves are commonly observed in the universe, space plasmas, and laboratory plasmas. In particular, collisionless shocks play significant roles in particle acceleration, for example, in Earth's bow shock and Supernova remnant shocks. In collisionless shocks, collisions between particles can not account for the formation mechanism and particle–field interactions are essential. Therefore, the shock thickness is much smaller than ion–ion mean free path and a large electromagnetic field exists at the vicinity of the shock. Laboratory experiments with high-power laser systems can be alternative to observations or in-situ measurement by satellites. Collisionless shocks have been produced and investigated in counter-streaming laser-produced plasmas[1]. They have been measured by optical diagnostics such as interferometry, shadowgraphy, optical pyrometry, and Thomson scattering to obtain the fundamental plasma parameters: density, temperature, charge state, and flow velocity[2]. Moreover, the measurement of an electromagnetic field is indispensable for collisionless shock experiments. Proton radiography is one of the methods to measure the field structures[3]. We will present recent measurements of the field structures associated with a shock formed in counter-streaming plasmas with proton radiography as well as optical diagnostics.

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O.Th_B7

Highly Radiative Shocks on the Laser Integration Line

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In this paper, recent experimental results on highly radiative shocks generated by the high-power LIL (laser integration line) laser facility are presented. LIL is the French MegaJoule Laser prototype delivering up to 10 kJ at 3 ω, located at CEA/Cesta near Bordeaux, France.

On over more than the ten past years, we have currently performed laboratory experiments [1-4] in connection with astrophysical phenomena in order to improve the physics understanding in the field of radiation hydrodynamics and also to validate numerical schemes and assumptions in numerical methods (verification and validation – V&V – procedure) and, very recently (December 2012), we have investigated on LIL, radiative shocks propagating in different gases (krypton and xenon) at low pressure (50 mbar). The used pushers were of two types containing either titanium or tin and the cross section of the cell where the shock propagates were about 1 mm^2.

All the diagnostics are visible (interferometry, self-optical pyrometry, 2D snapshot imagers) providing measurements of the shock and precursor velocities, temperature, electronic density and 2D shock front shape. The propagation of the radiative shock has been observed on more than 10 ns and shock velocities larger than 150 km/s have been inferred.
These experimental results will be compared with numerical results computed with 2D radiation simulation codes.

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Experimental evidence and theoretical investigation of photoionized plasma under x-ray radiation produced by an intense laser

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In recent years, several experiments have been carried out to generate photoionized plasmas in laboratory[1]. The photoionized plasma, which had been produced by high intensity lasers, represents miniature models of X-ray binary systems, active galactic nuclei, and quasi-stellar object absorbers. Several computer codes were composed to simulate the photoionized plasmas both under laboratory and astrophysical conditions, to study the underlying physical processes [2, 3]. In particular, the Heα and its satellite play important role in the analysis of spectra from the photoionized plasmas.

We present an analysis of the relative importance of the various atomic processes in photoionized plasmas on the Heα and its satellites as a function of the electron temperature and irradiation conditions [4]. In particular, we investigate the influence of K-shell photoionization of Li-like ions on the Heα spectrum and that of Be-like ions on its satellites. It is found that in photoionized plasmas these inner-shell processes have significant contribution under low radiation temperature and/or intensity, when Li- and Be-like ions are highly abundant but highly ionized H-like ions are rare.

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O.Th_C5

Physics and Technology for Engineering and Power Plant in Laser Fusion Energy Systems under Repetitive Operation

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Different proposals of Laser Fusion Energy have been envisioned in the last years. Those concepts cover from Engineering Facilities at large scale in Energy, to Power Prototyping and final DEMO Reactors. HiPER (Europe), LIFE (USA) and LIF_T (Japan), and other Chinese or Russian initiatives, are entering a new phase where is critical the integration of systems (lasers, target design, manufacturing and injection, chamber and blanket, tritium handling and Power cycles). The study of an Engineering Burst (in HiPER) facility with a repetitive laser operation, with realistic burst mode of hundreds to thousands of shots at 5-10 Hz rate, and small gain under continuous (24/7) repetition (Prototype) or final high gain Demo Reactor is finished and presented indicating its importance. It could be important the difference between Prototype and Demo, because the different target energy gains could have consequences in the first wall and optics. The Engineering Test Bed results will be able to demonstrate with the lowest risk**,** repetitive laser-injection systems in an already defined model of Chamber. Assuming those conditions, we have started to work how could be possible to accommodate Experiments in Technology relevant for Prototype and Reactor. This paper shows the differences in designing the chamber for single shot operation (NIF or LMJ Ignition/Gain machines), or repetitive systems, from Laser requirements to Chamber area, activation and damage in optics, wall and structural materials and also dose assessment. A summary of the differences in new designs from Engineering, Prototyping and Demonstration approaches will be the key goal. It will presents integration of the various systems needed for an early demonstration of laser-driven power production, including the requirements of tritium and neutron breeding, use of existing reactor-capable materials and considerations of plant safety. Our approach uses two levels: research in each one of the key questions from fundamental to applied physics and technology; and integration of our available answers into a Power Plant System for defining progressive designs from burnup: to thermo-mechanical responses of materials; fluidynamics; tritium generation and cycle; accident analysis after evaluation of activation and radionuclide concentrations, safety and radioprotection. That is a modelling integrating systems with help of specific proposed experiments.

O.Th_C6

Abstract for IFSA2013 (Focal distance variation due to neutron dose on silica final lenses for IFC)

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Nowadays, inertial fusion experimental facilities are devoting their efforts to the demonstration of the scientific viability of fusion laser energy. These facilities aim to prove ignition. Achieving this goal is essential in the roadmap to commercial laser fusion plants. HiPER (High Power laser Energy Research) [1] is the European project for the development of inertial fusion energy. The HiPER final goal is the construction of a facility for operation in continuous mode (HiPER 4a) and subsequently a pre-commercial power plant (HiPER 4b) [2]. Although different possibilities are open, currently, HiPER opts for a shock ignition scheme with 48 laser beams [3] with silica transmission final lenses at 8 m from the target explosions.

In Ref [4], we studied the neutron effects on the HiPER final lenses and found that under commercial power plant conditions (150 MJ target yield at 10 Hz) the lenses reach temperatures above tolerable operation limits. In addition, under relaxed operation conditions (50 MJ target yield at 1 Hz) the final lenses will present a non-uniform steady state temperature profile that will lead to optical aberrations. These aberrations hinder the operation of the optical system proposed for HiPER.

In the present work, we study the effect of these aberrations on the optical system proposed for HiPER. We will show that it is necessary an active strategy to keep the temperature profile as smooth as possible during the start-up of the power plant and during normal operation. Finally we will present different strategies based on a minimization of the aberrations induced on the laser spots. As a main conclusion, an active heating system will be necessary for every final lens to assure their acceptable performance.

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O.Th_C7

Buffer Gas Effects on Aerosol Formation and Hydrogen Co-deposition in a High-Repetition Rate Inertial Confinement Fusion Reactor

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Considerable attention has lately been directed towards the conceptual design of an inertial confinement fusion DEMO reactor with a high-repetition rate of implosion. Along with repeated implosions, however, the interior of target chamber is exposed to intense pulses of X-rays, unburned DT-fuel particles, He-ash and pellet debris. As a result, wall materials will be subjected to ablation, emitting particles in the plasma state. Ablated particles will either be re-deposited elsewhere or collide with each other, perhaps in the center-of-symmetry region of chamber volume. Colliding ablation particles may lead to the formation of clusters to grow into aerosol, possibly floating thereafter, which deteriorates the subsequent implosion performance via laser scattering, etc. Proposed for the LIFE Engine [1] most recently to mitigate chamber wall ablation is the use of buffer gases such as Xe at pressures ~0.1 Torr which, however, will be difficult to maintain due to the ionization under reactor operating conditions. Aerosol formation and tritium co-deposition would thus be affected by the plasma, but probably in a yet-to-be explored manner.

Over the past several years, a series of laboratory-scale experiments have been carried out to investigate the behavior of colliding ablation plasma plumes [2, 3, 4]. Used for these experiments is a laser ablation setup, referred to as LEAF-CAP (for the Laboratory Experiments for Aerosol Formation by Colliding Ablation Plumes), where two arc-shaped targets are irradiated in vacuum simultaneously by 3ω-YAG laser beams line-focused along the arc at 10Hz, each for 6ns, at power densities up to ~10J/cm^2. These targets are positioned in such a way that laser-ablation plasma plumes intersect with each other in the center-of-arc (CoA) region, diagnosed by a Langmuir probe, ion mass spectrometry, visible spectroscopy, CCD and ICCD cameras. Examined as the target materials are selected candidate wall materials, including C, W, Li and Pb.

In the present work, these LEAF-CAP experiments have been continued in weakly ionized inert gas plasmas of Ar, He and Xe with the electron temperatures around 1eV and densities of the order of $10^{8\text{-}9}$1/cc. It has been found from the visible spectroscopy and CCD camera observations for carbon targets that the rate of C_2 cluster formation in the CoA region, the key to carbon aerosol growth [3], decreases inversely with the increase in partial pressure of the buffer gas, whether or not it is ionized, which indicates the effect of atomic and molecular reactions.

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O.Th_C8

Progress toward a unified experimental kJ-machine CANDY

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To realize the Inertial Confinement Fusion (ICF) power plant, one key issue is a high-repetition-rate laser of kilojoules or greater. Others are the fuel fabrication and high-repetition injection, and ignition-high gain physics. Power plant technology, such as an innovative wall materials, will need to be developed. We divide the roadmap for achieving a fusion plant into three phases. The zeroth phase involves developing 1-kJ drivers. No fuel compression is considered. The _rst phase is to develop a breakeven machine that uses a 100-kJ driver. Here the fuel is compressed to 100x the solid density or more. The second phase is to demonstrate a commercial reactor. The fuel may be compressed to around 500x. The zeroth goal is to construct an unified experimental machine CANDY. DT cryogenic fuel pellet is injected at 10 Hz, to which the counter implosion beams are engaged, followed coaxially by the fast heating beams. Neutron Yield is $5x10^{12}$/shot and energy gain is 0.3%. A liquid Pb-Li blanket is to catch some mount of neutrons and radiations. We have developed a laser-diode-(LD-)pumped laser system HAMA with a repetition rate of 10 Hz [1]. We will use the fast-ignitor scheme, as reported partially in [2]. We have done the LFEX-GXII fast ignition experiment at OSAKA to test this scheme. LFEX heated the pre imploded core of a deuterated polystyrene shell target, resulting in $5x10^{8}$ DD neutrons. This value is significantly higher than the yields obtained from the previous fast-ignition experiments. LFEX increased the core temperature by a factor of more than two, i.e., from 0.8 keV to 2 keV. We also present the target injection and engagement results for the first time [3]. Related posters are presented in the same session.

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P.Th_1

Experimental study of hydrodynamic processes in indirect drive foams on "Iskra-5" iodine laser

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ABSTRACT

Experimental studies of hydrodynamic processes in indirect drive foams on "Iskra-5" iodine laser are presented in this report. Foam samples were irradiated in cylindrical channel by hohlraum X-ray flux. The shock velocity inside channel wall was determined by registration of the moment of UV radiation appearance at the lateral surface. This moment was registered by fast streak camera. The temperature was determined from shock velocity value in Al sample. Results of temperature distribution measurements along vacuum and foam channels are presented. The theoretical analysis of the experiments on X-ray radiation interaction with materials and hydrodynamic processes in samples was carried out.

P.Th_2

Theoretial study of hydrodynamic processes in indirect drive foams on "Iskra-5" iodine laser

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Experimental studies of hydrodynamic processes in indirect drive foams on "Iskra-5" iodine laser are presented in the report N.V.Zhidkov at al. Foam samples were irradiated in cylindrical channel by hohlraum X-ray flux. The shock velocity inside channel wall was determined by registration of the moment of UV radiation appearance at the lateral surface. This moment was registered by fast streak camera.

The theoretical analyzing of the obtained results is presented in this report. The transport of laser and x-ray radiation is simulated at 2D setting taking into account the degree of plasma ionization, gas- dynamic movement of the medium, electron and ion heat conduction and energy exchange between electron and ion in plasma.

P.Th_4

2D radiation-hydrodynamic simulations of hohlraum targets driven by intense laser beams

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Today, multidimensional codes, which combine the solution of the fundamental hydrodynamic equations with the spectral transfer equation for thermal radiation and with an accurate scheme for thermal conduction, provide an indispensable tool for the design and the analysis of experiments as well as for the understanding of physical phenomena at high energy density. The main motivation for the development of the new radiation-hydrodynamics code RALEF-2D (Radiative Arbitrary Lagrangian-Eulerian Fluid dynamics in two Dimensions) [1] was to support the undergoing and future research at GSI and at the upcoming FAIR accelerator facility [2].

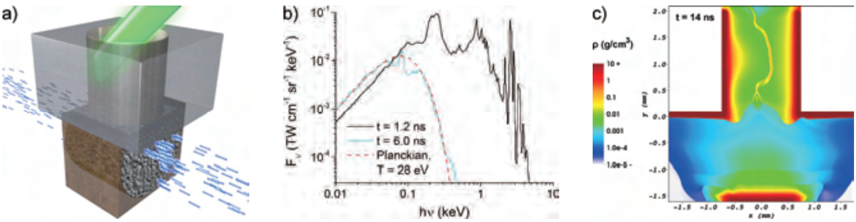

Fig. 1: a) Hohlraum-foam target for measurements of the heavy-ion stopping in hot plasmas,
b) Simulated x-ray spectra as would have been observed through the lower hohlraum hole,
c) Color contour plot of the matter density ρ in the simulated x-y plane at t = 14 ns

The unique combination of a high-power Petawatt laser facility and a large-scale accelerator for heavy ions at GSI offers a wide-spread area of physical applications. Important examples are undergoing experiments for measurements of the heavy-ion stopping in laser-generated dense plasmas at high temperatures. These measurements are of crucial importance for the indirect drive scenario of heavy-ion fusion and for the ion-driven fast ignition concept. Figure 1a shows one of such experimental configurations [3] where the PHELIX laser shots with a frequency-doubled 1.4 ns long pulse and a total energy up to 180 J inside a cylindrical hohlraum gold layer. The outgoing thermal x-rays heat a low-density foam to probe the ion-stopping inside a homogeneous carbon plasma. Figs. 1b and 1c show the results of the corresponding RALEF-2D simulations [4] for the x-ray spectra as would have been observed through the lower hohlraum hole and for the density distribution in the simulated plane.

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P.Th_5

The 2D simulation of cryogenic target compression and thermonuclear burn for the asymmetry of a radiation field in Rugby-type hohlraum

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It is known, that use of a hohlraum in the form of a ball for Rugby [1, 2] allows saving up to 25 % of laser energy in comparison with a cylindrical hohlraum for laser of megajoule scale. In work [3] it was offered to use this economy for an increase in the relation of the radius of the hohlraum case to the radius of the spherical target placed in the centre of a hohlraum. The calculations of Rugby-hohlraum performed with the 2D SINARA code [4], have shown, that such approach allows not only to facilitate conditions of achievement of necessary symmetry of a X-ray flux on a surface of a spherical target, but also it could considerably reduce overlapping of internal laser cones by a material of a flying target ablator [3]. It would allow avoiding problems with necessity of a transfer of additional laser energy to internal laser cones for maintenance of necessary symmetry of X-ray flux on a surface of a spherical target. Notice that a difficultly simulated nonlinear effect based on Stimulated Brillouin Scattering (SBS), namely, the effect of crossed-beam energy transfer (CBET) is used for this purpose in the experiments executed on NIF [5-6].

The results of numerical modelling of indirect drive targets for thermonuclear ignition on megajoule lasers are presented in the report. Calculations were performed with use of the 2D codes of a radiation gas dynamic developed in RFNC-VNIITF [4, 7]. Requirements to accuracy of target manufacturing and X-ray flux symmetry were studied by means of the 2D TIGR-OMEGA-3T code [7]. The 2D- simulations of target compression and burn were performed with this code for X-ray flux asymmetry obtained in the 2D SINARA code calculations executed for Rugby-hohlraum with taking into account spectral kinetic radiation transfer.

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P.Th_6

Repetitive-mode Fast-Ignition Fusion mini-Reactor CANDY -Overview of developing component technologies and present status of tailored pulse laser irradiation system-

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Successful 1.85 MJ laser irradiation conducted by National Ignition Facility (NIF) in 2012, achievement of a controlled fusion burn and gain using the single-shot mega-joule class laser is within a scope. Following an effort of this scientific proof of ignition, engineering development needs to start on inertial fusion energy (IFE) based on repetitive-mode experiments. In this engineering phase, development of an IFE driver is the first priority, because the design and size of the IFE experiment machine are decided by the energy or power of the IFE driver. A diode-pumped solid-state laser (DPSSL) is a promising candidate as a reactor driver for IFE because it can be operated at a high-repetition rate (>10 Hz) with high efficiency (>10%). Based on available DPSSLs as represented by HALNA or Mercury, we can develop a repetitive IFE experiment machine by including the other indispensable IFE technologies of target injection and an energy-conversion system, which are both available. This is a promising path for realizing a nuclear fusion power plant step by step [1]. To realize this integrated IFE machine, we first developed the DPSSL-pumped laser HAMA [2] to demonstrate repetitive fusion reaction [3] and fast heating inertial confinement fusion (ICF) in which both implosion and heating pulses are required [4]. In addition, we recently included a target injection system into HAMA and succeeded in the fusion reaction by irradiating the laser on the flying CD beads targets [5]. These repetitive-mode ICF experiments inspire a positive image of how IFE machine works in the future; those were hardly supposed from conventional single-shot experiments. These demonstrations trigger the upgrade of DPPSL technology from 20 J/10 Hz to 1 kJ/10 Hz output. Following this on-going DPSSL upgrade, we are ready for design a kJ-class repetitive-mode Fast Ignition Fusion mini-Reactor: CANDY. In this presentation, I describe the overview of developing component technologies of CANDY. In addition, I also describe the tailored pulse laser irradiation system.

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P.Th_8

Direct heating of imploded plasma in the fast-ignition scheme

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We propose a new scheme of the fast-ignition, in which the heating laser irradiates an imploded plasma core directly. In the conventional scheme, after the shell is imploded into the highly dense plasma core by the compression laser, an ultra-intense-short pulse laser irradiates the inside of the cone, thus generating fast electrons. These fast electrons heat the core, when they move towards the core. Consequently, the temperature of the core plasma is raised high enough to ignite the thermonuclear burn. In order to minimize the required energy of the heating laser as shown in Fig. 1, the energy coupling efficiency from the heating laser to the imploded core plasma must be improved.

If we assume that dependence of fast electron transport on its kinetic energy with the range of the core-heating fast electrons is weak, the energy coupling efficiency is expressed by a product of four factors; (1) the energy conversion efficiency from the laser to the forward-moving fast electrons, (2) the transmittance of the fast-electrons through the tip of the cone, (3) the energy coupling efficiency between the tip and the core, and (4) the energy deposition fraction from the fast electrons to the core when the fast-electrons are moving through the core plasma. Since the heating laser directly irradiates the core in our proposed scheme, we can remove two of the above mentioned four factors, namely, (2) and (3). As the result, the net energy coupling efficiency is expected to increase. Also, the fast-ions will heat the imploded core plasma as well as the fast-electrons. We have already conducted experiments following this direct irradiation scheme, using LFEX laser and GXII laser in ILE, Osaka University, and we have observed higher neutron yields of D(d,n) ^{3}He. In this presentation, we will explain modeling of the direct heat fast-ignition.

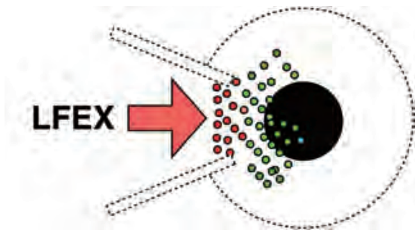

Fig. 1 Schematic of direct heating.

This work is partially supported by JSPS Grant-in-Aid for Scientific Research (C).

P.Th_9

Observation results of X-ray emission from the core at the fast-ignition scheme fusion by using the LFEX laser with counter-illumination toward CANDY

Yasuhiko NISHIMURA[1,5], Yoshitaka MORI[1], Ryohei HANAYAMA[1], Katsuhiro ISHII[1], Suisei Nakayama[1], Shinichiro OKIHARA[1], Kazuhisa FUJITA[1], Takashi SEKINE[2], Nakahiro SATO[2], Takashi KURITA[2], Toshiyuki KAWASHIMA[2], Hirofumi KAN[2], Osamu KOMEDA[3], Naoki NAKAMURA[3], Takuya KONDO[3], Manabu FUJINE[3], Hirozumi AZUMA[4], Tatsumi HIOKI[4], Mitsutaka KAKENO[4], Tomoyoshi MOTOHIRO[4], Atsushi SUNAHARA[6], Yasuhiko SENTOKU[7], Eisuke MIURA[8] , and Yoneyoshi KITAGAWA[1]

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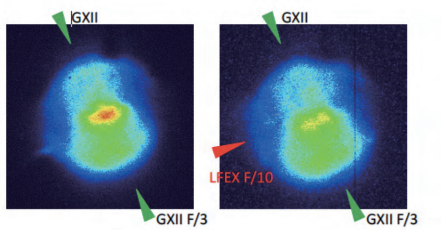
We are doing research and development aiming at the early realization of a compact laser fusion experimental reactor (CANDY). In the latest research, the basic experiment of the first-ignition scheme by the counter-illumination by using Diode pumped solid state laser. This experiment obtained a core overheating by a compact system [1]. Based on this result, we performed the first-ignition experiment by counter-illumination scheme by using GEKKO GXII (GXII) and the Laser for Fast Ignition Experiment (LFEX) laser institute of laser engineering, of Osaka University. A spherical deuterated-polystyrene shell was polarly pre-imploded by two counter-beams (1.3ns-515 J) of the GEKKO XII green laser. We thenfocused the 600-J LFEX laser onto the nakedcore from the side, vertical to the laser axis overa period of 1.5 ps.

The X-ray pinhole photographs in Fig.1 (a) and (b) show that along the GXII beams axes, the emission width (time-integrated) is 360 mm FWHM, while the width is 230 mm along the LFEX axis, so that the LFEX absorption point is 0.6xcloser to the core than expected in the uniform implosion. In the uniform implosion scheme, the core width should be 360 mm in any direction. The photograph in Fig.1 (b) shows no apparent change with injecting the LFEX except the core emission decreases. Since the spectral window is limited from 2 to 3 keV, the decrease implies that the core emission is higher than 3 keV, leading to the core temperature of higher than 1 keV. In this case, LFEX, which demonstrated that the most intense laser in the world directly heats the core and achieves the highest DD neutron yields (5 x10^8 neutrons) ever obtained in fast-ignition scheme. In comparison with the neutron yields (6 x 10^5) in the absence of LFEX heating, the LFEX laser increased the yield by a factor 1000.



(a) w/o LFEX (b) with LFEX

Figure 1. X-ray pinhole camera photograph.

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P.Th_10

Target Monitoring and Plasma Diagnosis using 2ω probe beam for CANDY

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To realize repetitive-mode fast-ignition fusion mini-reactor which we named CANDY, we have conducted a series of fusion reaction experiments with highly-repetitive diode-pumped laser system. Our roadmap for realizing a nuclear fusion power has been shown in the literature [1]. First, we developed the DPSSL-pumped laser HAMA [2] to demonstrate repetitive fusion reaction [3] and fast heating inertial confinement fusion (ICF) in which both implosion and heating pulses are required [4]. In addition, we recently included a target injection system into HAMA and succeeded in the fusion reaction by irradiating the laser on the flying CD beads targets [5]. In this report, we show some experimental results of target monitoring and plasma diagnosis using shadowgraph with second-harmonic of heating pulses laser.

Figure 1 shows a snapshot of an injected target irradiated by the HAMA laser which is captured 2ω probe 300 fs in pulse length. The laser energy on the target is 1 J, and the pulse duration and are wavelength are 300 fs and 800 nm, respectively. In Figure 1, the laser is focused on the surface, blowing the plasma off. Figure 2 shows the image of the double foil at the moment of plasma collision. A 4-J 0.4-ns output of a laser-diode-pumped high repetition laser HAMA is divided into four beams, two of which counter illuminate double-deuterated polystyrene foils separated by 100 μm for implosion. The remaining two beams, compressed to 110 fs for fast heating, illuminate the same paths. 2ω 100-fs probe captures the double foil image at 1.3 ns after the peak of the imploding beam, when the imploded plasmas collide with each other and form the core.

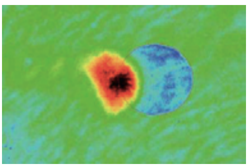

Figure 1: Snapshot of an injected target.

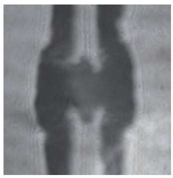

Figure 2: Image of the double foil at the plasma collision.

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P.Th_11

Repetitive Pellet Injection and Irradiation toward the Repetitive-mode Fast-Ignition Fusion mini-Reactor CANDY and Neutron Generation

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Pellet injection and repetitive laser illumination are key technologies for realizing inertial fusion energy [1-4]. Neutron generator using lasers also requires a repeating pellet target supplier. Here we present the first demonstration of target injection and neutron generation [5]. We injected more than 1300 spherical deuterated polystyrene (C_8D_8) bead pellet targets during 23 minutes at 1 Hz (Fig.1). After the pellet targets fell for a distance of 18 cm, we applied the synchronized laser-diode-pumped ultra-intense laser HAMA. The laser intensity at the focal point is 5×10^{18} W/cm^2, which is high enough to generate neutrons. As a result of the engagement, we produced 2.45-MeV DD neutrons. Figure 2 shows the neutron time-of-flight signals detected by plastic scintillators coupled to photomultipliers. The neutron energy was calculated by the time-of-flight method. The maximum neutron yield was $9.5 \times 10^4/4\pi$ sr. The result is a step toward fusion power and also suggests possible industrial neutron sources.

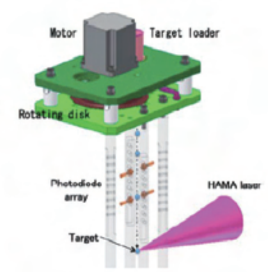

Fig. 1: Target injection system.

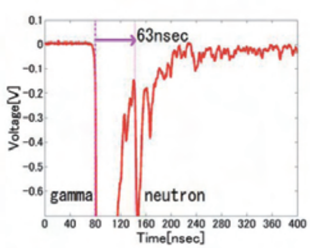

Fig. 2: Neutron generation.

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P.Th_12

Accuracy Required for the Target Injection in the Method of the Beam Steering with FWM

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In direct ICF, it is necessary to irradiate a target with high power laser beams. The laser beams have to be steered for the accurate laser irradiation since it is difficult to inject the target in the allowable margin of error. The method of beam steering with phase conjugate (PC) mirrors is one of the candidates [1]. In the method, probe beams whose energies are low enough not to damage it are illuminated the target. The diameters of the beams are expanded larger than the expected positions of the target. The scattered beam (seed beam) by the target is amplified and enters into the PC mirrors. The PC beam is generated in the opposite direction of the seed beam. The PC beam retraces the same path for the property. Therefore, it is amplified and irradiated the target. When the PC beam comes back, the target has moved several hundreds micrometers because of the high speed. It is necessary for the PC beam to be compensated for accurate irradiation to the target. Four wave mixing is used as the way of the compensation of the PC beam. In four wave mixing, the interaction of two counter-propagating pump beams and a seed beam generates a PC beam of the seed beam. The angle between a seed beam and a PC beam is proportional to the angle between two pump beams [2]. It is possible to adjust the PC beam in order to compensate the moving distance of the target by setting the angle between two pump beams. The compensated distance of the phase conjugate beam at the target position is dependent on the target position, the angle between two pump beams, and the focal lengths of the lenses of the laser system but not the optical path. With the parameter of the components of GEKKO XII, the angle is 4.5 mrad when the moving distance is 100 μm. If the allowable margin of the laser irradiation is ±10 μm, that of the target position in the direction parallel to the optical axis has to be ±0.3 mm. In the perpendicular direction, the allowable margin of the target position is limited by the optical length and the diameter of the amplifiers and has to be ±0.4 mm. As a result, the injection accuracy needs to be within ±0.3 mm.

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P.Th_13

Alternative Schemes to Realize Fast Ignition Inertial Fusions with Modifications of Target Injection Methods and Reactor Chamber Configurations

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This paper describes a new proposal to realize the inertial fusion energy production truly with the so-called fast ignition target. Although there are lots of sub-divisional subjects for this aim, only a few of them are described here. Key words are (1) Injection methods for fast ignition cone targets, (2) Arrangements of chamber components including target injection machine and final optics, and (3) Erosion thresholds of various surface materials for reactor chambers. The rests are hopefully clarified in the near future, after the associated experts establish a new organized group and start the activity.

In the discussion session during the Japan-US Workshop held at ILE, Osaka University, several years ago, the author noticed that the simple-minded long distance propagation of the fast ignition target from the injection source to the center of the reactor chamber was not possible. The reason was that the fluid mechanical unstableness in the chamber could not allow such target propagation. After this time until now, the author looked for a feasible and realistic way for the chamber arrangements with the scheme modifications. After the long consideration, the author arrived at a new scheme as follows

The cone target is injected into the reactor chamber and the ignition laser light irradiates the inner surface of the cone after the main compression laser pulse arrival at the fusion fuel sphere. Although the both injection axes of the target and the fast ignition laser must be aligned as the best scheme, the locations of both heads cannot be placed simply at the center of the same chamber side. This means that the both heads must be located at the different sides of the chamber center during the propagation. As the result, the cone edge comes at the front side of the target, while the target sphere comes at the rear side. This flight scheme along the long distance is rather unstable, because the fluid dynamic force on the whole body of the target, especially on the cone cannot stabilize the small change of the target axis from the unstable neutral regime. To demonstrate this, a model cone was dropped from the height of about several meters, and the status of the landing on to the earth level was monitored with a camera. Almost all landings after propagations were not acceptable for the fast ignition status, while only a small rare case was the acceptable range. These results urge us for the target to be injected into the chamber under the fuel sphere at the head side during the flight.

Under the axes aligned case as above, the target injection head front is located at the central position at the chamber entrance, while the ignition laser is launched from the peripheral fringe section of the larger concave optical component. On the contrary, there is an alternative laser injection method with non-aligned axes, if the non-uniform cone irradiation is allowed. This is the second candidate replaceable from the above first case.

In any case, the front end of the target injection machine must be located at the place as near as possible to the chamber entrance, because the distance between the front end and the chamber center must be made as short as possible. If the front end must be placed so, the material surface strength including the surface erosions of the front components is expected as high as possible. This causes us to gather the mechanical strength of various candidate materials in more detail with this aim. The author group has continued these database fulfillments until now. Those results are also shown during the meeting.

P.Th_14

Possibility of Ultradeep Penetration of Fragments of Thermonuclear Targets

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Operation of scientific facilities, igniting thermonuclear microexplosions, and IFE power plants can be accompanied by the formation of the high-density, high-velocity objects of several kinds [1-3]. These objects will damage the optical elements and/or other construction elements if the special measures are not taken [1-3]. It is evident that for the optimization of such measures, the information about the parameters of the high-velocity objects and the processes of their interaction with the construction elements is highly desirable. We will consider the problems related to the so-called ultradeep penetration of fragments of thermonuclear targets and the importance of this effect for optimization of the designs of some of the scientific ICF facilities and IFE power plants.

The ultradeep penetration is the penetration of the projectile in the solid target on the very large depth d_p of the order of $(10^2$ to $10^4)d$, where d is the typical transversal size, for example, diameter, of the projectile [4,5]. The observed values of d_p are up to about 100 mm [4]. The ultradeep penetration is possible when several conditions are satisfied [4,5]. For example, d should be about 100 μm or less, the velocity of the projectile at the time when it hits the target should be greater then about 1 km/s [4,5], in Ref. [4] its upper limit of about 3 km/s is also presented. The fragments with such parameters can arise when the yield of thermonuclear microexplosion is not sufficient for the complete evaporation of the high-density target materials, for example, hohlraum walls and cones. One more condition of the ultradeep penetration is that the average density of the cloud of the projectiles should be sufficiently high [4,5]. Arising of such clouds due to the low yield thermonuclear microexplosions seems to be possible.

If the chamber in which the microexplosions occur is not filled with gas, the danger of any target fragments will be especially high. However, motion of the dangerous fragments in the gas seems also to be possible. Probably, in some situations small fragments can arise relatively close to the equipment and chamber walls due to decay of larger fragments. Note that the effect that is similar to the ultradeep penetration can probably result in penetration of some fragments through the liquid protecting the walls of the reactor chamber.

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P.Th_15

Laser fusion for fuel breeding

Wallace Manheimer (retired from NRL) and Ralph Moir (retired from LLNL)

Even if a 1 MJ laser like NIF achieves a gain of 100 (higher than most LLNL estimates) and upgrades the laser efficiency to 10% (current efficiency closer to 1%) and pulses at 15 Hz (currently 1-2 shots per day), it could hardly be a means to economical fusion, considering its cost and size, where only 1/3 of the power goes to electricity (500MW) and of this 150 MW is needed to power the laser. But let's be a bit more pessimistic, let's say development stops short and the gain is 50 and the laser efficiency is 5%. Then there is no power at all for the grid.

Unless laser efficiency and target gain can be significantly upgraded, what laser fusion needs is a way to make these estimates economical.It would be more helpful still if laser fusion could fit in easily with current energy infrastructure. This paper will show that the tremendous potential of fission suppressed hybrid fusion, or more briefly fusion breeding, is that it offers exactly that potential [1,2]. It will discuss fusion breeding and show how it might offer a solution to the energy dilemma within a reasonable time. The optimistic parameters for the system in the previous paragraph could well produce fuel economically, even the more pessimistic ones might. The amount of nuclear fuel available is in dispute; some estimates give more than a century's worth; others, much less. What is indisputable is that only about 1% of uranium and 0% of thorium is available for today's reactors. Fusion breeding makes more than 50% of each available. The fusion breeding we propose is quite different from the LIFFE (Laser Inertial Fusion Fission Energy) formerly advocaed by LLNL [3]. LIFFE has a fusion reactor deep inside a fission reactor. The scheme we propose breeds fuel for existing reactors, which have been in use for 50 years and have a constantly improving utilization and safety record.

The breeding reactions (for T and ^{233}U) are exothermic, so reactor power roughly doubles. But more important is the fact that a single fusion breeder reactor can produce nuclear fuel (4% ^{233}U mixed with 96% ^{238}U) for least 5 light water reactors (LWR's) of equal power. Thus a NIF sized device (at a laser efficiency of 5-10% and a gain ~50-100) can be an end in itself, rather than a stepping stone to who knows what, decades and decades later. As a fuel producer, fusion is an order of magnitude more prolific than fast neutron reactors like the integral fast reactor (IFR). But IFR's can burn the actinide wastes of about 5 LWR's of equal power. This is a reasonably mature technology, at least compared to fusion. Proliferation risk of the raw fuel is minimized by immediately diluting the 233U, produced in the thorium cycle, with 238U; and that of the spent fuel, by immediately separating out the actinides, and then burning them. Both would be done in a highly secure local facility, so there is no long time storage or long distance travel of material with proliferation risk. The combination of fuel production by fusion, power production mostly by LWR's and actinide waste burning by IFR's have the potential of generatingmany terawatts of carbon free electrical power, economically, environmentally soundly, and with little or no proliferation potential; at least as far into the future as the dawn of civilization was in the past.

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P.Th_17

Diffusion of H isotopes in a W first wall for a direct drive laser fusion reactor

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The laser inertial fusion project HiPER (High Power laser for Energy Research) plans to use tungsten (W) as a first wall material to protect the reaction chamber from the fusion products, in particular high energy ions. Those ions, mostly H isotopes and He, get implanted in the first micrometers of the W armor which, in addition to the thermo-mechanical and atomistic damage, will eventually cause swelling and prohibitive tritium (T) concentration if they are not released. Thus, the understanding of the diffusion and retention of fusion ions inside the W first wall is critical in the construction of a reactor.
This work presents a study of the most relevant aspects for the modeling of the diffusion of light species under pulsed mode laser fusion conditions. The importance of the temperature, (both the background constant one and that pulsed after each shot), the surface/diffusion limits, the lack of reliable simulation parameters (diffusion, dissociation and recombination constants as well as Arrhenius activation energy values) and the role and evolution of trapping sites will be discussed. First estimates on the diffusion, release and concentration of the implanted H isotopes in W will be shown for two HiPER reactor designs and working conditions, corresponding with phase 4a and phase 4b. These results will help not only to determine the maintenance protocols and to predict the replacing cycles of W armors but also it will help to assess the implications of T accumulation from the point of view of recovery, safety and management strategies.

P.Th_18

Numerical Analysis of Plasma Behaviors in a Magnetic Thrust Chamber for Laser Fusion rocket

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Keywords : Laser Fusion Rocket (LFR), Laser-produced plasma, Magnetic field

A period of the mission in space must be as short as possible, since people who are trying a manned space flight beyond Mars will be suffered from exposure to cosmic radiation due to the long stay in space. Conventional rocket engines, which are chemical propulsion rockets, are powerful but bad fuel consumption rates. Much fuel is required for the round trip to Mars. On the other hand, Electric propulsion rockets: Ion engines, MPD arcjets, have good fuel consumption rates. But, the thrust of them is small due to the limitation of the power supply in space. That is, it takes long time to reach the Mars by using electric propulsion. Laser fusion Rocket (LFR) is an attractive candidate for the manned Mars mission, since the LFR offers a large thrust with high specific impulse owing to the enormous energy released by a fusion reaction with little amount of fuel. [1] In the LFR, propellant was expelled using magnetic thrust chamber, as shown in Fig.1.

A final goal of this study is to build design law of the LFR. We have been developing a numerical analysis 3D hybrid code for the simulation of high energetic plasma in the magnetic thrust chamber, and it showed high performance of the LFR. For the validation of this code, we have performed simulation experiment: we observed the interaction between Laser-produced plasma which simulate the high energy plasma by fusion, and magnetic field. However, the results of the experiment are not in good agreement with those from the calculation. This would be due to the difference of the initial plasma condition, especially ion energy distribution, of the laser produced plasma in between experiment and numerical analysis. Therefore, producing process of laser plasma is added by using a one-dimensional radiation hydrodynamic code. Figure 2 shows impulse bit obtained by using the revised code. The target is 500 µm diameter sphere and incident laser energy is 4 J. The estimated impulse bit is 18 µNs.

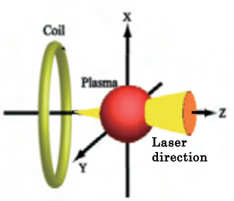

Fig. 1. Calculation Model

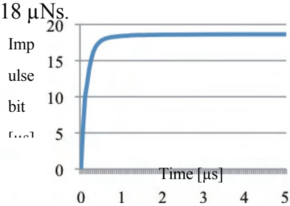

Fig. 2. Graph of Impulse bit

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P.Th_19

Numerical simulation of vortex generation by laser energy deposition in a gas

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Intense laser systems have been widely used in many fields. Recently, compact laser system has developed [1]. The laser system has opened new fields, such as laser-induced combustion in engine [2], and laser-induced breakdown has attracted much interest again [3]. Laser-induced breakdown and plasma expansion strongly depend on the laser power, energy, pulse length, and so on. Fluid dynamics after laser energy deposition in gases is important in the combustion. Especially, we have been interested in the vortex properties after shock wave propagation from a hot spot by laser breakdown [4,5].

In order to study the gas dynamics after shockwave propagation, we have developed the two dimensional hydrodynamic simulation code based on the CIP scheme [6]. Using the simulation code, we study the influence of the aspect ratio and the energy density of the hot spot, which initiates the shockwave, on the gas dynamics passing shock wave. The difference in the vortex profiles by the asymmetry of the hot spot is also presented.

This work was supported by JSPS KAKENHI (22540512).

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P.Th_20

Investigation of the harmonic generation and direct heating mechanisms at the interaction of high intensity ultra short laser pulses with an overdense aluminum plasma layer

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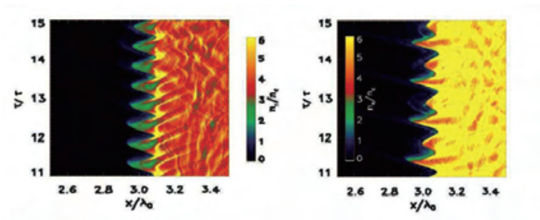
The relativistic interaction with dense matter turns out to be a highly non-linear multi-particle multiphoton problem that cannot be treated by traditional optical and plasma perturbation theory but requires full kinetic treatment. Simulations based on the Particle-in-Cell (PIC) method have been most fruitful in mapping out the new asymptotic features. Most spectacular results are the generation of ultra-bright highly collimated beams (relativistic electrons, ions, X-rays, and a host of secondary nuclear beams) and very efficient generation of high harmonics from solid surfaces. Harmonics generated with *fs* laser pulses are among the most intense sources in the wavelength range of a few tens of nanometers, being a coherent source much brighter than the other XUV sources, apart from the XFEL.

This paper presents results from detailed simulation of the interaction of high intensity, short pulse duration (*fs*) laser beam with an overdense, pre-ionized and steeply bounded aluminium plasma layer. The plasma is treated kinetically, solving the relativistic equations of motion for a set of electrons and ions incorporated within a macroparticle. The laser intensity ranges within 10^{17} *to* 10^{22} W/cm^2 tapping the plasma both at normal and oblique incidence. Various pulse durations have been considered while the intensity and the polarization of the laser beam were varied. The initial electron density, normalized to the critical density, was set in a range 1-15. Simulations with the 1D3V particle in cell LPIC++ code reveal strong oscillations of the critical surface driven by the normal component of the laser field and by the ponderomotive force. By reflection on this oscillating surface, the incident laser pulse causes the occurrence of high order harmonics.



a b

We show in Fig.1. the oscillating overdense plasma surfaces as output from the code. Fig.1a is obtained at normal incidence with a laser field strength of $a_0 = 1$, $I\lambda^2 = 1.37 \cdot 10^{18} Wcm^{-2} \mu m^2$, tapping on a plasma with $n_e / n_c = 4$ and Fig.1b corresponds to the oblique incidence ($\alpha = 30°$) of the same *p* polarized laser pulse incident on a plasma with $n_e / n_c = 7$.

We will report results from detailed calculation of the effect of incident laser pulse polarization on the harmonics spectra. Harmonic emission increases with the laser intensity and when lowering the plasma density. In case of oblique incidence pulses, harmonics are emitted into a broad angular interval and have been found to be sensitive to the *s* or *p* polarization of the incident pulse. As a consequence of the direct heating, a *p*-polarized incident laser beam is far more efficient in accelerating the electrons within the plasma. Details of the work will be presented. Presenting author: <u>**Tara Desai**</u>

P.Th_21

Validation of the technique to fabricate cryogenic targets for Fast Ignition by IR method

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A new technique for fabricating a D_2 cryogenic-layered, cone-attached target with thickness uniformity over 99 % for fast ignition experiment has been proposed. Since deuterium is a stable isotope, conventional beta-layering cannot be applied [1], furthermore because of the attached cone, it is very difficult to fabricate the uniform layer of D_2 ice. An additional infrared (IR) laser heating [2] and thermal controlling of the cone temperature are proposed to control thickness uniformity of the D_2 ice layer.

An integrating sphere installed in a cryostat has been designed as shown in Fig.1. The ray trace in the integrating surface with the 95-% reflection diffusion surface with the diameter of 12. 7 mm was simulated. The energy of the IR laser required to generate the calorific power equivalent to the beta-layering was estimated to be about 2 mW.

On the other hand, the additional temperature controlling Au-cone is needed because the cone produces geometric asymmetry of heat flux. Figure 2 (a) shows temperature gradient along the inner surface of D_2 ice in the case without temperature controlling the cone. Figure 2 (b) shows that heating the cone with the energy 553 nW remove the temperature gradient. The additional heating the cone with the energy 552-554 nW was calculated to be required for achieving thickness uniformity over 99 %. The detailed conditions of the simulation will be presented.

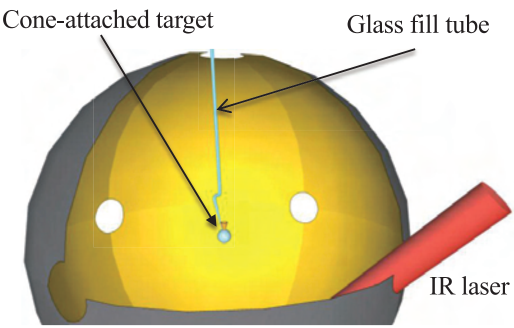

Figure 1: The irradiation system of the target

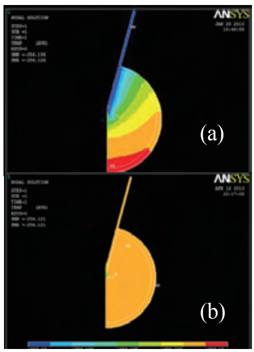

Figure 2 (a) : Temperature variation without temperature controlling. (b) : Temperature variation with 553 nW cone heating. The temperature difference between red and blue is 11 mK in both maps.

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P.Th_22

Development of tritium doped plastic target for laser fusion

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Tritium-doped, deuterated-polystyrene (CD-PS) targets for laser fusion experiments are desire to be developed. It is reported that illuminations of ultra-violet (UV) light enhance exchange reaction between tritium and deuterium in CD-PS [1], however gradient tritium distribution was observed in optical direction. This is because UV light less than 275nm can enhance only surface of targets.

In this study, the wavelength dependent photochemical yield of the reaction was measured by irradiating a CD-PS tube in a tritium atmosphere with UV light of 200-300nm. The UV was emitted from a D_2 lamp and diffracted with a grating. Tritium distribution in the CD-PS tube after 2hours irradiation was measured with imaging plates. Figure 1 shows the comparison of the tritium concentration and calculated absorbed light energy. The solid line shows the tritium signal and the thick solid line shows absorbed energy which well agrees with the tritium concentration. This result clearly shows that the reaction was enhanced by additional UV light illumination. Figure2 shows photochemical yield against wavelength. Thin solid line shows photochemical yield and the thick solid line shows transmission of CD-PS. UV light with the wavelength of around 280nm was confirmed to be a significantly large peak of photochemical yield of the reaction. The around 280 nm UV light is favorable for our aim because the transmission of the CD-PS at 280nm is high, thus the homogeneous doping along the optical path can be expected. We concluded that the UV light with the wavelength around 280nm is most effective for doping tritium into CD-PS target. The detailed result of analysis will be presented.

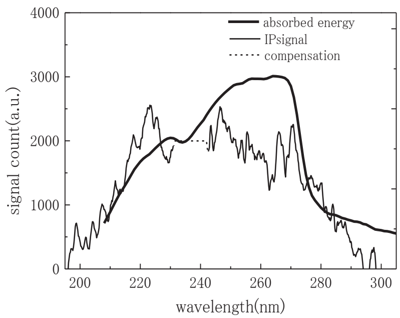

Fig. 1: tritium signal and absorbed energy

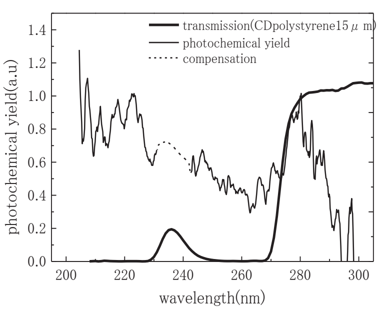

Fig. 2: photochemical yield and transmission

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P.Th_23

Development on brominated deuterated-hydrocarbon capsule for reducing Rayleigh-Taylor instability

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Suppression of hydrodynamic instabilities is very crucial for the ultimate goal of inertial fusion energy (IFE). A high-Z doped plastic of brominated polystyrene ablator is a very promising candidate to suppress the ablative Rayleigh–Taylor (RT) instability in a directly laser-driven IFE target [1] because bromine atoms in the corona plasma emit strong radiation due to intense laser irradiation, then the radiation drives the radiative ablation front inside a plastic target.

We have been developing a brominated deuterated-hydrocarbon capsule for reducing RT instability [2]. The required concentration of bromine is 3.3 wt% (0.29at%) for reduction of RT instability, thus brominated deuterated-polystyrene was mixed with non-brominated deuterated-polystyrene in order to adjust the bromine content. In this case, there is a problem of low viscosity of the brominated deuterated-polystyrene dissolved solution and the previous double-nozzle emulsion generator could not keep the emulsion shape such low viscosity state. Therefore, we carefully examined and developed a double-nozzle emulsion generator, especially 2nd-nozzle (outer nozzle), finally we obtained a new double-nozzle emulsion generator with wide viscosity range. The brominated deuterated-polystyrene capsule which we fabricated with the new double-nozzle emulsion generator is shown in Fig.1. The diameter and thickness of the shell were 489μm and 7.6μm. The bromine composition in the capsule was analytically measured to be 3.30 wt%. The detail of the new double-nozzle emulsion generator will be discussed in the presentation.

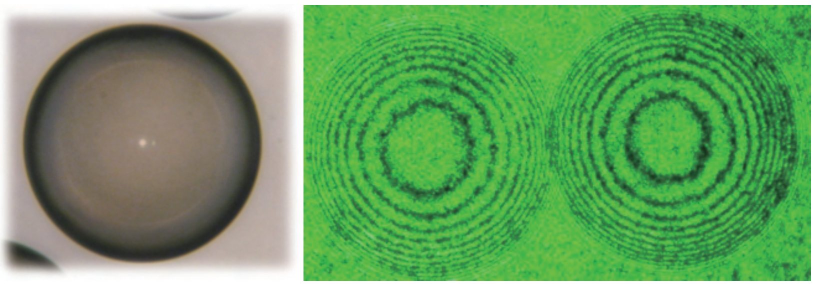

Figure 1: Photograph (left) and Interference patterns (right) in a brominated deuterated polystyrene shell. The diameter and thickness of the shell were 489μm and 7.6μm. The bromine composition in the capsule was measured to be 3.30 wt%.

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Modern trends in low-density materials for fusion

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Nowadays the following distinct trends seem to prevail in low-density target manufacturing techniques.

1. Nanostructuring and uniformity are combined with wide range of densities requested, from 1-2mg/cc (gaseous-like) to more than 100 mg/cc. This is quite challenging from the point of view of solid state physics.
2. Polymer foams give way to plastic aerogels. Fine uniform materials are needed for easy simulations and comparison with experimental results. Thinning structure of foam brings us to aerogels. Plastic aerogels are now available for manufacturing within certain range of parameters. Different experimental techniques are used for extremely low and for moderate densities.
3. Metal nano-snow sometimes sintered for better stability. Low-density metals proved efficient in some application.
4. Combinations and topologic modifications are possible. Composites, nanograss, metal in plastic aerogel matrix are the examples. In fact the structures diversity used in shot experiments came to some desired standards, where aerogels remains the preferred form.

We report our targets of all the four trends mentioned.

Low-density targets prove very fruitful in driver-plasma experiments. For decades they continue to yield new experimental data and to put new unsolved questions for original experimental schemes. The experiments with them are presented in the paper submitted to Laser and Beam Plasma Interaction section.

Several developments for aerogel target fabrication could be considered. Several types of high-Z nanoparticle dopants with different properties may help to explore increasing uniform compression. Steps in density profile ranging from subcritical (about 2 mg/cc) to 100 mg/cc are reported for higher hydrodynamic efficiency of targets. Layers with density gradient could be applied for experiments on equation-of-state of the matter. Concentration profile of high-Z nanoparticles in aerogel layers is planned for increasing target efficiency, and for efficient x-ray converters.

P.Th_25

Magnetic Sabot Remover for Polystyrene-Target Injection

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IFE target is required to inject the reactor at the laser-focused position with demanded velocity and accuracy. The target cooled down to cryogenic temperature is protected from thermal degradation by insulator sabot. Figure 1 shows the experimental setup for sabot remover from target. A target, 4 mm diameter polystyrene sphere was inserted in 40 mm length aluminum sabot. The polystyrene target with the sabot was accelerated up to 40 m/s by the pneumatic gun or coil gun[1] [2].

The sabot is decelerated by interaction between the magnetic field and induced eddy currents. It was removed from the target and fell down to the bottom of vacuum chamber. The separated target was shot against the backend of vacuum chamber. The distribution of ten shot target is indicated in Fig. 2. Its deviation σ_x is 29 mm and σ_y is 24 mm. Because of correlation with sabot deviation, the sabot stability during deceleration should be improved.

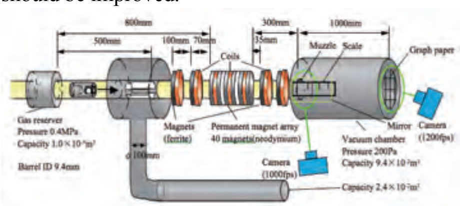

Figure 1: Experimental setup for sabot removal.

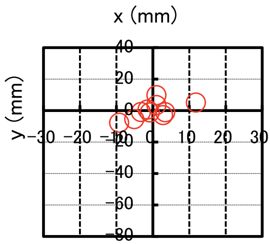

Figure 2: Target shot position at the backend of vacuum chamber

The laser shot experiment is prepared with self laser steering FWM(Four Wave Mixing) system[3]. It has no mechanical steering including compensation of target traveling in seed laser duration time.

References

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[3] N. Kameyama, H. Yoshida, Fusion Science and Technology: 63, 120 (2013)

P.Th_26

Target and Sabot Separation and Tracking in Injector

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IFE targets are injected to the reactor after separation from a sabot that protects the target form radiation heat. The target injection accuracy has dependency on the accuracy of sabot accelerated by a pneumatic gun or a coil gun and decelerated by a permanent-magnet-array [1] [2]. The decelerated sabot velocity is proportionally decreased with the distance from the frontend of permanent-magnet-array[2]. In order to track the sabot from the outside of injector, currents are detected by pickup coils winded among the permanent-magnet-array. As shown in Fig. 1, its waveform is a function of sabot shape and velocity. The sabot position and velocity can be measured. A metal or metal-coated spherical target was used for a substitution for a polystyrene target to analyze separation from a sabot. A target, 4 mm diameter steel sphere was separated from 40 mm length aluminum sabot in Fig.2 experiment. The sabot velocity is effectively decreased. The target separation from sabot is decided to occur at the frontend of the permanent-magnet-array.

The laser shot experiment with this injector is conducted with self laser steering FWM(Four Wave Mixing) system[3].

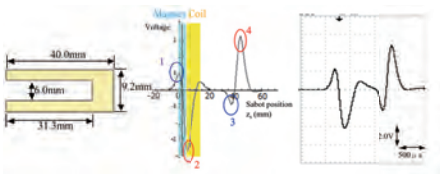
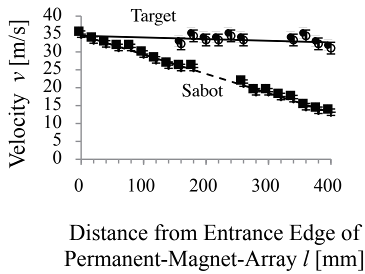


Figure 1: Experimental setup for sabot removal.



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[3] N. Kameyama, H. Yoshida, Fusion Science and Technology: 63, 120 (2013)

P.Th_27

10-TW high-contrast double CPA laser system for ion acceleration

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When a laser pulse with intensity well exceeding 10^{18} W/cm^2 irradiates a foil target, the laser-field-driven force accelerates electrons at the target surface up to relativistic velocity. A portion of the accelerated electrons passes through the target toward the rear side, resulting in generation of an electrostatic field, which accelerates ions at the target rear surface. The laser-target interaction can be complicated by the presence of an amplified spontaneous emission (ASE) pedestal at a leading edge of the high-intensity laser pulse. A nanosecond ASE pedestal with intensity of the order of 10^{12} W/cm^2 can heat the target causing its expansion and preplama formation. Several attempts have been made to decrease the ASE level by using a plasma mirror [1] or OPCPA laser system combined with a saturable absorber: J-KAREN [2].

In this work, we propose another way to improve the main pulse-ASE ratio by using a "double-CPA bypass line" system. Figure 1 shows the setup. We have developed a new laser line consisting of a pulse compressor, a saturable absorber, a pulse stretcher and a Ti:Sap. multi-pass amplifier. The most remarkable feature of this system is that the bypass line can be installed into a conventional TW laser system. In this work, we connected the bypass system between the Ti:Sap pre-amplifier and the final amplifier of JLITE-X [3], which originally generates ASE with a contrast level of 10^{-7} predominantly attributed to the regenerative amplifier.

The temporal profile of the laser pulse was measured by a third-order cross-correlator at the downstream of the saturable absorber. As a result, the ASE level was determined to be 2×10^{-10} of the main-pulse intensity at -500 ps before the main pulse.

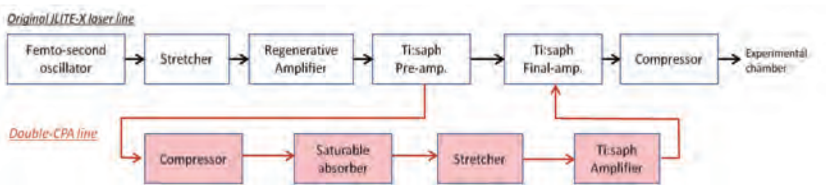

Figure 1: A setup of the laser system

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P.Th_28

Characterization of Cluster-Gas Targets and its Application to Laser-Driven Particle Acceleration Experiments

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In laser-driven ion acceleration, efficient generation of high energy ions up to 50 MeV per nucleon has been achieved using cluster-gas targets [1,2]. In these experiments, we have employed a three-staged conical nozzle which was designed based on the Boldarev's model for preparing a sufficient amount of submicron-sized clusters at room temperature [3]. In such experiments, the detailed knowledge of the initial target parameter is the key to understanding the acceleration mechanism in the laser-cluster interaction.

In present study, we have evaluated the sizes of CO_2 clusters, which formed in the supersonic expansion of CO_2/He or CO_2/H_2 mixed-gas, by measuring angular distributions of Mie scattered light from the clusters. As the results, the mean sizes of CO_2 clusters are estimated to be 0.22 μm and 0.25 μm for the cases of CO_2/He and CO_2/H_2, respectively [4]. The results are consistent with the Boldarev's model.

At present, the real-time detection of ion beam with several tens of MeV is technically difficult, while that of high energy electron beam, which leads to the ion acceleration, is available. Therefore, we have tried to search optimal conditions of the ion acceleration by measuring the electron energy spectra by changing the focal positions inside the gas jet. Figure 1 shows the electron energy spectra measured with the laser-irradiated H_2 gas + CO_2 cluster target at the focal positions of on-axis (y = 0 mm) and off-axis (y = 0.6, 0.95 mm). The electron energy spectra vary significantly depending on the focal positions, which suggest that the focal position suitable for the ion acceleration could exist. In the presentation, with the knowledge of the initial target parameters of cluster-gas targets, we will discuss the optimal conditions of the ion acceleration.

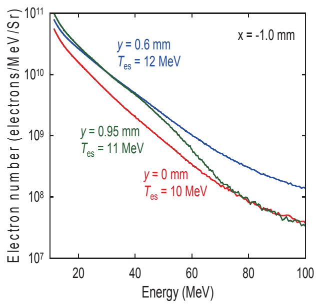

Fig. 1. Focal position dependence of electron energy spectra.

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P.Th_29

Bunching of Laser-Produced Proton Beam in Laser Plasma Interaction

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In intense laser plasma interaction, several issues still remain to be solved for future laser particle acceleration. In this paper we focus on a bunching of ion beam, which is produced by a laser plasma interaction. In this study, a structured solid target (see Fig. 1) [1,2] is illuminated by an intense short laser pulse. A strong electric field is generated at the target rear side. We have successfully obtained a bunched beam in our particle-in-cell simulations in this paper. Figure 1 shows the bunching device employed. The ion beam velocity tilt is reduced as shown in Fig. 2 (a).

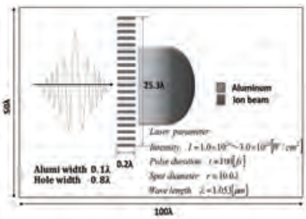

Figure 1: Simulation model

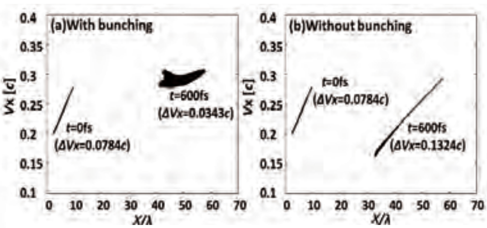

Figure 2: The acceleration ion beam is introduced to the bunching device. (a) With bunching device. (b) Without bunching device.

Acknowledgements: This study is party supported by MEXT, JSPS, CORE (Center for Optical Research and Education, Utsunomiya Univ.), ASHULA project (JSPS Asia Core to Core Program: Asian Core Program for High Energy Density Science Using Intense Laser Photons), and ILE/Osaka University.

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P.Th_30

Ion Beam Control in Laser Plasma Interaction

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A remarkable ion energy spectrum is demonstrated by the inductive continuous post-acceleration in a laser plasma interaction together with TNSA (Target Normal Sheath Acceleration) [1]. An intense short-pulse laser generates a strong current by high-energy electrons accelerated, when an intense short-pulse laser illuminates a plasma target. The strong electric current creates a strong magnetic field along the high-energy electron current in plasma. During the increase phase of the magnetic field, the longitudinal inductive electric field is induced for the forward ion acceleration by the Faraday law. By the four-stage successive acceleration, our 2.5-dimensional particle-in-cell simulations demonstrate a remarkable increase in ion energy by a few hundreds of MeV; the maximum proton energy reaches 254MeV. The inductive acceleration in the multi stages provides a unique controllability of the ion energy and its energy spectrum.

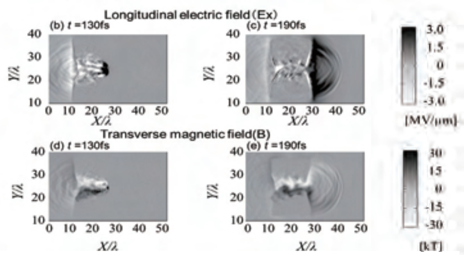

Figure 1: The inductive acceleration field is clearly generated in a near-critical density plasma: the laser generates a strong electron current, and at the increase phase of the current the inductive field is generated. The moving speed of the inductive field in the plasma is matched to the pre-accelerated ion beam speed for the continuous and efficient acceleration.

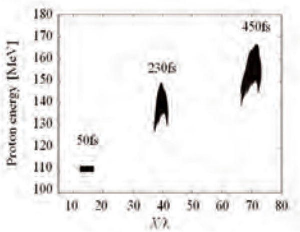

Figure 2: The inductive acceleration field accelerates pre-accelerated ions continuously and efficiently. The ion beam energy distributions at *t*=50fs, 230fs and 450fs for the near-critical density plasma target. At *t*=50fs, the ion beam is not yet accelerated.

Acknowledgements: This work is partially supported by MEXT, JSPS, CORE (Center for Optical research and Education, Utsunomiya Univ.), ASHULA project (JSPS Asia Core to Core Program), and ILE/Osaka Univ. The authors also would like to extend their acknowledgements to Prof. J. Limpouch, Prof. O. Klimo, Prof. A. Andreev, Prof. K. Tanaka and Prof. Z.M. Sheng.

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P.Th_31

Collimation of Laser-Produced Proton Beam

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In intense laser plasma interaction, several problems remain to be resolved. In this paper we focus on a collimation of ion beam, which is produced by a laser plasma interaction[1]. In this study, the ion beam is collimated multiple thin plasma targets (see Fig. 1)[2]. The plasma electrons neutralize the ion beam charge. The gaps among the thin plasma prevent the electron current, which could neutralize the ion beam current. Therefore, the ion beam self-magnetic field contributes to the ion beam collimation. We have successfully obtained a collimated beam in our particle-in-cell simulations. Figure 1 shows the collimation device employed. Figure 2 demonstrates that the multiple thin plasma targets realize the ion beam collimation.

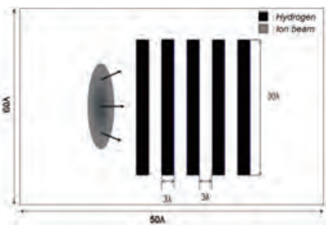

Figure 1: Simulation model for the collimation of laser-produced proton beam.

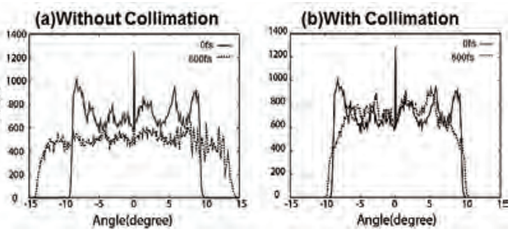

Figure 2: Angular distributions of beam ions (a)without the collimation and (b)with the collimation.

Acknowledgements: This study is party supported by MEXT, JSPS, CORE (Center for Optical Research and Education, Utsunomiya Univ.), ASHULA project (JSPS Asia Core to Core Program: Asian Core Program for High Energy Density Science Using Intense Laser Photons), and ILE / Osaka University. We would also like to appreciate Dr. S. M. Lund, R. H. Cohen, P. Ni and B. G. Logan for the idea of the many thin foils' collimation.

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P.Th_32

Ion Acceleration by Ultra-intense Laser Pulse Interacting with Near Critical Density Plasma

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Ion acceleration schemes driven by ultra-intense laser pulse and near critical density plasma interactions are presented. They include high energy electron beam driven ion acceleration with uniform near critical plasma [1], large quantity ion beam generation by persistent Coulomb explosion regime [2] and enhanced BOA (breakout after burner) through double-layer target with different densities. It is found that the well-collimated ion beams with the maximum energy higher than 1 GeV and several nC charge quantity are acquired through the above schemes. At the same time, the energy transfer efficiency between pulses and ions are also effective. The investigations and discussions are based on 2.5D PIC (particle-in-cell) simulations.

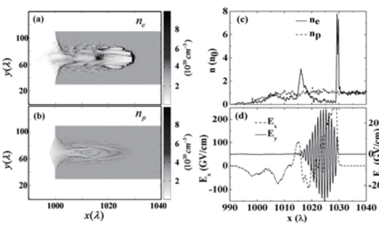

Figure 1: Strong ponderomotive force provided by the laser pulses expelled the background electrons and formed an electron cavitation. The unneutralized ion bunch expanded under the Coulomb pressure. A significant amount of protons are expanding in the backwards direction.

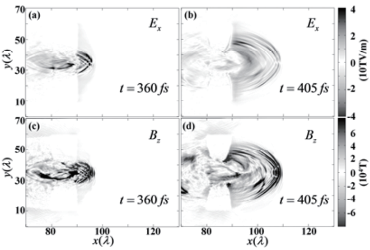

Figure 2: A dipole magnetic field moving with the electron beam is induced by the current. When the electron beam penetrates throughout the second target, the magnetic field rapidly expands in vacuum. Therefore, a quasi static electric field is generated with the expansion of the magnetic field.

Acknowledgements: This work was partly supported by NSFC (No. 11175048) and Shanghai Scientific research innovation key projects No. 12ZZ011. Support from China Scholarship Council, the JSPS and MEXT Program, and the CORE of Utsunomiya University are also acknowledged.

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P.Th_33

Particle acceleration with laser pulses and proton beams

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We present our recent experiment results of proton acceleration with high contrast TW [1] and PW laser systems. The effects of the prepulse on plasma density profile and proton acceleration are analyzed in detail. The angular distribution of the energetic protons is discussed. It is found that the energetic protons go slightly away from the normal direction. In order to obtain protons of energy larger than 10 TeV, we propose to use TeV protons as the powerful driver to excite a strong plasma wake. The transversal defocusing of the witness protons inside the wake field is overcome by using a narrow plasma channel. We also discuss a new concept of inertial confinement fusion driven by laser accelerated electrons. Since it is the electrons instead of laser pulses directly drive the fusion, all kinds of efficient laser, even long wavelength laser, may be applied.

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Dominant deuteron acceleration with high-intensity lasers for neutron generation and isotope production

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Experiments on the interaction of a 15 TW, 400 fs laser with heavy-water ice-covered thin copper foil, at an intensity of 2×10^{19} W/cm^2, were performed demonstrating the generation of a "pure" deuteron beam with a divergence of 20º, maximum energy of 8 MeV, and a total of 3×10^{11} deuterons with energies above 1 MeV - equivalent to a conversion efficiency of 1.5±0.2% [1]. Subsequent experiments on neutron generation from d-d reactions in a "pitcher-catcher" geometry and the irradiation of a ^{10}B sample with deuterons resulted in a neutron flux of $(4\pm1)\times10^5$ neutrons/sterad and the production of ~ 10^6 atoms of the positron emitter ^{11}C, respectively.

Other experiments at the HERUCLES laser facility (50 TW, 40 fs, double plasma mirror operation) at an intensity of 1×10^{21} W/cm^2 have produced neutrons with energies up to 16.8 MeV in directional beams utilizing the Li(d,n)Be reaction in a "pitcher-catcher" geometry from D_2O ice-covered 800 nm Al targets [2]. The neutron yield was measured to be up to $(1.0\pm0.5)\times10^7$ neutrons/sterad with a flux 6 times higher in the forward direction than at 90º. The neutron yield and spectrum were compared to that for d(d,n)He and Li(p,n)Be reactions. Monte Carlo simulations were performed to model the neutron spectra and to better understand the experimental results.

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P.Th_35

Numerical simulations of proton beam characteristics for ELIMED Beamline

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ELI-Beamlines will be the high-energy, repetition-rate pillar of the ELI (Extreme Light Infrastructure) project. The main objective of the ELI-Beamlines Project is delivery of ultra-short high-energy pulses for generation and applications of high-brightness short pulse X-ray sources and accelerated particles. ELIMED (MEDical applications at ELI) beamline should demonstrate the capability of laser-based particle accelerators for medical applications, mainly for proton radiotherapy of tumours which requires a sufficient number of accelerated protons with energy about 60 MeV at least.

In this contribution, we study the acceleration of protons by laser pulse with parameters accessible for ELIMED beamline. Our goal is to estimate maximum energies of accelerated protons, the number of high-energy protons, and their divergence by means of two-dimensional particle-in-cell simulations. The calculations have been performed for 30 J laser pulse in 30 fs (1 PW) focused to the spot size of 3 μm at FWHM (intensity 1.4×10^{22} W/cm^2) and for 15 J pulse (0.5 PW) with the same length and beam width (assuming the decrease of intensity about 50% to 7×10^{21} W/cm^2 by using double plasma mirror to improve the laser pulse contrast). The laser pulse interacts with polyethylene (CH_2) planar foils of thickness 200 nm or 1 μm and with specially designed targets with nanospheres or gratings on their surface (already used in experiments at lower intensities).

In our simulations, we observed higher energies of protons for linear than for circular polarization. Oblique incidence of the laser pulse on target does not seem to be favourable for proton acceleration at such high intensities as the accelerated protons are deflected from target normal axis and their energy and numbers are slightly decreased. Slightly higher proton energies and numbers are predicted for thinner foils (200 nm) and 0.5 PW pulse compared with thicker foils (1 μm) interacting with 1 PW pulse. On the other hand, the number of high-energy protons can be substantially (several times) increased by introducing a microstructure (deposited nanospheres or grating) on the front surface of a thicker foil. The expected numbers of accelerated protons in the energy interval 60 MeV±5% are calculated between 10^9 and 10^{10} per laser shot with estimated proton beam divergence about 20º (FWHM).

P.Th_36

Nanotube Accelerator for Generation of High-Quality Proton Beams

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Ion acceleration driven by ultraintense ultrashort laser pulses has been intensively studied in the past decade because a number of future applications are expected. For practical use of the accelerated ions, it is crucial to produce high-quality beams that are monoenergetic and collimated. We here propose a novel ion acceleration scheme using carbon nanotubes (CNTs), in which embedded fragments of low-*Z* materials are irradiated by an ultrashort intense laser to eject substantial numbers of electrons. Due to the resultant unique electrostatic field, the nanotube and embedded materials play the roles of the barrel and bullets of a gun, respectively, to produce highly collimated and quasimonoenergetic ion beams.

Figure 1 shows the schematic view of a nanotube accelerator. The double nested nanotubes are irradiated by an ultrashort intense laser pulse. The outer carbon nanotube is chemically adsorbed with heavy atoms such as gold, while the inner nanotube is made of light materials such as hydrogen and carbon to form the projectiles. After blowing off the electrons, the remaining nanotubes composed of positive ions generate a unique electrostatic Coulomb field so that the inner ions are accelerated along the axis symmetrically toward both ends of the outer nanotube.

Figure 2 shows temporal evolution of the proton energy spectrum in the axial (solid curves) and radial (dashed curve at $T = 5$) directions obtained by three-dimensional molecular-dynamic simulations, where T denotes time normalized by the laser cycle. The size of CNT is only 30 nm. As a result quasimonoenergetic protons with an energy of 1.5 MeV are produced. If the hydrogen atoms are replaced by carbon atoms, the maximum ion energy increases to 10 MeV for the same target structure. The maximum energy can also be increased by enlarging the target size.

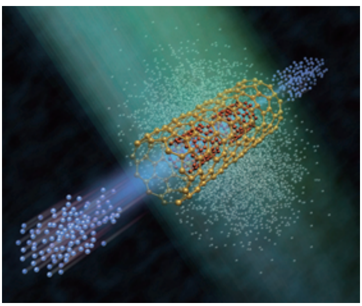

Fig. 1: Schematic of a nanotube accelerator

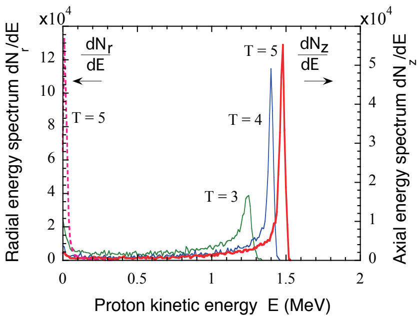

Fig. 2: Temporal evolution of energy spectrum.

P.Th_37

Laser ion acceleration and neutron source in short-pulse solid-nanoparticle interaction

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We here propose an efficient and stable high energy proton and neutron sources using solid nanoparticles. An intense laser light propagating around the nanoparicles can efficiently expel electrons from the solid-nanoparticles to generate a strong electric field to accelerate ions. We have succeeded to deliver repeatedly the solid-nanoparticles with a size of 100 to 500 nm in a diameter at the laser focus point with a number density of about 10^{10} cm^{-3}. These nanoparticles are much larger than the clusters used previously and thus can provide much higher ion energy than those obtained before.

We show 3d-PIC simulation results to present laser intensity dependence of the ion energies in a range of the normalized laser electric field from a = 1 to 100, corresponding to laser intensity approximately from 10^{18} to 10^{22} W/cm^2. In a range of relatively high intensity, $a > 10$, the radiation pressure accelerates electrons in the forward direction. Ions following the electrons become directional high energy ions with energy of 100 MeV. In a relatively weak regime, $a < 10$, the electrons expelled from the nanoparticles expand relatively uniformly, which generates MeV ions. Fusion cross section in D-D and D-T reactions has its maximum values in 1-3 MeV and 100-300 keV range, respectively. In this laser intensity range, it can be used as a stable neutron source. We will discuss the optimum size of the nanoparticles according to the laser intensity and the effects of prepulse and pedestal of the laser light on the ion acceleration.

We also show some preliminary experimental results using DPSSL-pumped high-repetition-rate 20-TW laser (MATSU-1). Solid nanoparticles of deuterated-polystylene are delivered at the laser focus point, where the laser intensity was about 10^{18} W/cm^2. A yield of ~10^5 neutrons per shot was stably observed during continuous 100 shots.

P.Th_38

Wave guided laser wakefield acceleration in splash plasma channels

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We study laser wakefield acceleration (LWFA) for generation of stable ultra-short electron bunches with a low beam divergence and a high charge. Such acceleration is a basis for high-temporal and high-spatial resolution imaging systems as well as the first stage of the ultra-high energy multistage acceleration technique.

Using of plasma channels in the wake field acceleration has been shown to provide a controllable self-injection that results in production of higher quality stable-electron beams. Moreover, the longer guiding of the laser pulses in a plasma channel leads to a higher energy of accelerated electrons.

We have demonstrated the process of formation of short-lived, deep, straight, and controllable plasma channels (splash plasma channels) produced by picosecond and sub picosecond laser pre-pulse in argon gas jets [1, 2]. To understand guiding ability of splash channels, PIC (Particle-in-cell) simulations which include ionization have been demonstrated. The quasi monoenergetic electron beams with their stability and parameters determined by splash channel structure can be generated. Splash channels may useful wave guided LWFA.

We are developing laser system which has double laser pulse for the channel guided LWFA in Photon Pioneers Center, Osaka University. Splash plasma channels can be produced by one of the laser pulse with its pulse duration sub-picosecond, and by another femtosecond high intensity (> 10^{19} W/cm^2) laser pulse for the acceleration of electron beams. In this presentation, we discuss our experiment plans and estimations of the channel guided LWFA.

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P.Th_39

Monoenergetic collimated nano-Coulomb electron beams from crossed laser beams interaction with a projectile

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High quality electron bunches can be widely used in synchrotron radiation facilities, free electron lasers, and high energy density physics. In this work two crossed laser beams are employed to accelerate a solid density projectile to obtain monoenergetic collimated high-energy high-yield electron beams. The two crossed laser beams, linearly polarized with opposite phases from each other, irradiate the electrons with incidence angles 5^0 and -5^0 with respect to the z axis, respectively. Along the z axis, the magnetic fields of the two beams cancel with each other, while the resultant electric field has only a nonzero axial component. The electrons can be directly accelerated by this axial electrical field. At $t=100T_0$, a central energy of 760 MeV has been achieved after a dephasing length of 97.4 μm, as shown in Figure 1(a). The corresponding acceleration gradient is as much as 78 GV/cm. During the whole acceleration process electrons in the bunch are in almost the same field phase, therefore the beams keep monoenergetic along the path. The full width at half maximum of the energy spectrum is 21 MeV, corresponding to an energy spread of 2.7%. The transverse electrical field E_x and magnetic field B_y vanish along the z axis, which makes the electrons have very small transverse momentums, as shown in Figure 1(b). As a result, the electron bunch with a divergence angle of 12.2 mrad is well collimated. Since the target has a solid density, finally about nano-Coulomb electrons have been accelerated to high energy. This electron yield is almost 5~8 times of that from wake field acceleration at the same energy level.

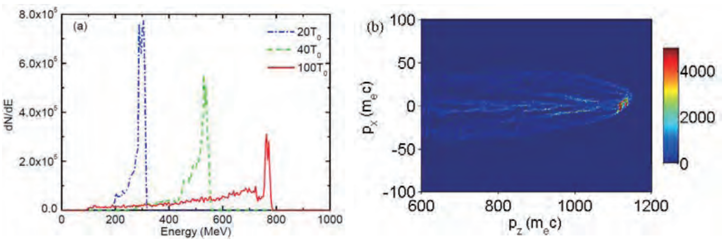

Figure 1: (a) Electron energy spectra. (b) Electron momentum distribution at $t=100T_0$.

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P.Th_40

Enhanced Electron Bow-wave Injection in Laser Wakefield Acceleration

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Abstract: A new regime of strong electron injection named electron bow-wave injection (EBWI) in laser wakefield acceleration of electrons has been investigated carefully by using the PIC code PLASIM. In that paper [1], it is found that the dense trapped electrons in a strong electron bow wave (EBW) contribute most to the injected electrons in the bubble. EBWI operates at higher laser intensities than that of the normal self-injection (NSI) of the electrons from the bubble periphery.

In this paper, we study the effects of transverse profile of incident laser on trapping of electrons in EBWI regime and find that the electron bow-wave injection can be enhanced further by using supper-gaussian laser. By using the PIC code PLASIM, we find that the super-gaussian profile laser pulse has larger transverse ponderomotive force compared with the gaussian pulse with the same laser intensity、total energy. The super-gaussian laser can drive more energetic electrons of the electron bow wave into the bubble with higher longitudinal injection velocity. At last, the total number of trapped electrons increases almost 6 times. And the quality of electron beam is also improved obviously.

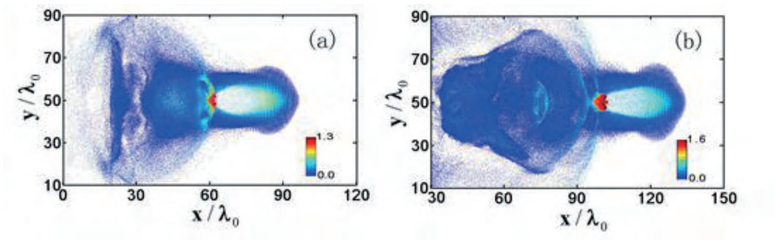

Figure 1: Electron energy density distribution for gaussian laser (a) and for super-gaussian laser (b) at $t = 108T_0$.

This work is supported by the NSAF (grants 10976031).

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P.Th_41

Measuring the Injection Rate in Ionization-Induced Injections of Laser Wakefield Accelerators

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In laser wakefield accelerator studies, the mechanism of ionization-induced injection of electrons has recently been proposed to have a few advantages over the self-injection such as lower laser power requirement, simplicity in target designing, better alignment and better reproducibility [1]. Studies on optimizing the output electron beam qualities have been booming ever since [2].

In this work, we studied the ionization-induced injection dynamics and measured the injection rate by two-dimensional particle-in-cell (PIC) simulations. In particular, a definite injection section is found with a radius of a few microns.

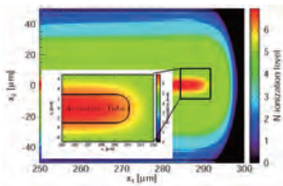

Figure 1: Injection section plots from PIC simulations.

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P.Th_42

Numerical modeling of multi-GeV laser-wakefield electron acceleration inside a dielectric capillary tube

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Laser guiding inside a dielectric capillary [1-2] tube offers a promising approach for building a multistage laser-wakefield accelerator. In this approach, a relativistic electron beam, produced externally, is injected into the wakefield, excited in the quasi-linear regime by the propagation of the laser pulse inside a gas filled dielectric capillary tube. A dielectric capillary tube, similar to optical fiber, can be used to guide the laser over meter long distances. Its main advantages over plasma channels are simplicity of construction and operation.

We have numerically investigated this scheme of laser-wakefield acceleration. Guiding of a short pulse laser inside a dielectric capillary tube over ~1-2 m long distances and acceleration of an externally injected electron bunch to ultra-relativistic energies (~5-10 GeV) are demonstrated in the quasi-linear regime of laser wakefield acceleration. Two-dimensional axisymmetric simulations were performed with the code WAKE-EP [3] that allows computationally efficient simulations of such long scale plasmas. The code extends the performances of the quasi-static particle code, WAKE [4], to simulate the acceleration of externally injected electrons, including beam loading effect, and propagation of laser beam inside the dielectric capillary tube. Details of code modifications along with numerical results demonstrating the generation of high quality ultra-relativistic electron beams inside a dielectric capillary tube will be discussed in this paper.

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P.Th_43

Controlled Generation of Dense Attosecond Electron Sheets in Laser Wakefields Using an Up-Ramp Density Transition

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Intense ultrathin electron source (few nanometer long, corresponding to attosecond duration) has been widely explored in the context of laser-plasma interactions, due to its high interest in probing dynamic systems with unprecedented resolutions, or in generating attosecond electromagnetic pulses. So far, most investigations have been focused on ultraintense laser interaction with soild plasma foils, where the obtained attosecond electron beams are directly accelerated by the laser field.

Here, we investigate a controlled scheme of generating overcritical dense attosecond electron sheets in laser-driven underdense plasma waves. By naturally introducing an up-ramp density transition profile in an underdense plasma cell, sharp quasi-one-dimensional (1D) electron injection occurs during the density transition to a following plateau, provided the drive pulse is sufficiently intense. This 1D injection is due to the fast switching of the wake's phase velocity near the transition point from above to well below the light speed c due to the highly nonlinear effect [1]. The density spike characteristic for wave breaking is then trapped in the first wave bucket and gets accelerated as a whole without much broadening [2]. A fairly broad laser diameter not only validates this scheme in higher dimensions, but also results in a sheet profile for the final trapped beam, which may be suitable for various applications, especially for coherent Thomson scatterings.

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P.Th_44

A diagnosis method of laser-accelerated protons using CR-39 in a field contaminated by photo-neutrons

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In laser-driven ion acceleration experiments using the cluster-gas targets, a significant amount of fast electrons, which drives the ion acceleration, are produced along with high energy ions with several-tens of MeV [1,2]. In our recent experiment using CO_2 clusters embedded in H_2 gas conducted with the J-KAREN laser facility (1 J, 40 fs) at JAEA-KPSI [3], the maximum energy of electrons reaches up to 300 MeV. Such high energy electrons could produce high energy photons via bremsstrahlung processes. Accordingly, the photons could produce photo-neutrons via a series of (γ, n) reactions. In order to diagnose the “laser-accelerated protons” exclusively in such photo-neutron contaminated fields, it is a crucial issue to evaluate the effects of photo-neutrons in CR-39 track detectors, because the CR-39 can also record etchable tracks of “recoiled protons” kicked out by the neutrons as “fake proton signals” [4].

In order to estimate the effect of photo-neutrons on the CR-39, we have measured the energy spectrum of laser-accelerated electrons produced from the H_2 gas + CO_2 cluster target by using magnetic electron spectrometer. The wide-spread energy spectra with the maximum energy of 300 MeV and the total charge of about 1 nC per one laser shot have been observed. In order to estimate the photo-neutron fluxes in CR-39 detector unit, we have conducted simulations using PHITS ver. 2.52 [5], which is a Monte Carlo particle transport code including the evaluated cross sections in the giant resonance regions for photo-neutron reactions, where the experimentally observed electron energy spectrum was employed as an initial condition.

Based on the simulation results, we have designed the configuration of the CR-39 detector unit and beam dump for high energy electrons to minimize the effect of photo-neutrons.

In addition, we have developed the analysis technique of CR-39 based on the etch pit growth behavior, which can practically discriminate the “genuine etch pits” created by laser-accelerated protons from “false etch pits” created by the photo-neutrons. This technique in combination with the PHITS code results allows us to obtain the reliable information on laser-accelerated protons using the CR-39 even in the photo-neutron contaminated fields.

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P.Th_45

Generation of high-quality 200 keV class quasi-monoenergetic electron beam driven by weakly-relativistic optical field

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A 200keV class quasi-monoenergetic electron bunch using density ramp scheme[1] was observed at weakly-relativistic optical field condition. 1.7-TW laser beam with 40 fs pulse duration was used to create such optical field ($a_0 \sim 0.4$). An electron bunch was observed from He gas-jet with Gaussian density profile (neutral gas density: $1.5\text{x}10^{19}$ cm^{-3} and density scale: ~500um) (see in Fig. 1(a)). Here, a number of electrons was estimated to be ~10 pC/shot. In particular, the transverse momentum spread was estimated to be $\Delta p/p=1.6\text{x}10^{-2}$ by the measurement of spatial distribution (see in Fig. 1(b)) and the energy measurement (Fig.1(a)). This result shows that high repetition rate (>100 Hz) "plasma cathode electron gun" can be realized by using high-repetition-rate terawatt laser system [2].

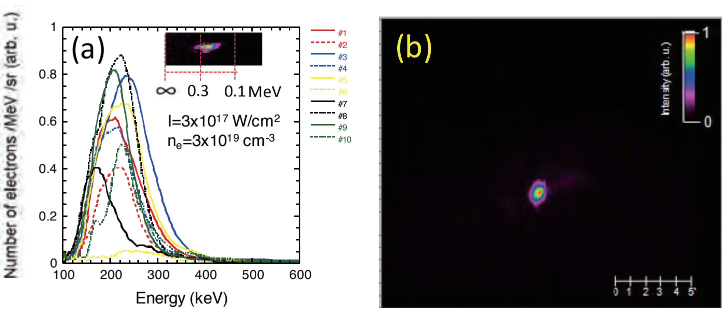

Figure 1. (a) Energy distribution of the electron beam (10 sequential shots(#1-#10)). (b) Typical electron image.

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P.Th_46

Estimation of Fast Electron Orbit in Gradient Magnetic Flux Density

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The generation of high energetic ion beams in the interaction of ultra-short laser pulses with foil targets are a rapidly growing research area. These ions are accelerated from the rear surface of the foil target by the sheath potential driven by an intense laser light, which is called the target normal sheath acceleration [1-3]. In this scheme, the sheath potential is generated when the fast electron escapes from the target. Therefore, the measurement of fast electron is important to the generation of high energetic ion.

The electron spectrometer is one of the simple diagnostics to measure the energy of fast electrons [4,5]. When the magnetic flux density can be considered as a constant, the electrons move according to simple Larmor motion determined by the fast electron kinetic energy. Therefore different energy electrons reach on the different positions in the detector, the electron energy distribution can be easily obtained. However, the initial rise profile of magnetic flux density becomes the gradient profile by the effect of magnetic-field leakage. In the low energetic electron, this gradient of magnetic flux density could be affected in the energy spectrum. Therefore, we calculate about the effect of fast electron orbit in the gradient magnetic field using the numerical-analytical approach. Moreover, we estimate about the electron energy spectrum measured the using gradient magnetic flux density.

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P.Th_47

Laser-Plasma Based Neutral Atom Acceleration from Solid Targets

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The basic requirement for the acceleration of charged particles is an electric field; - for example, an RF cavity in conventional particle accelerators and the quasi-static charge-separation electric fields [1] or wakefields [2] in laser-plasma-based accelerators. The above techniques become ineffective to accelerate neutral atoms as they do not respond to an electric or a magnetic field. However, if neutral atoms are first ionized, then accelerated in an electric field and finally neutralized by putting back all the electrons, it can lead to a neutral atom accelerator. This has been recently achieved in an argon nano-cluster via charge-exchange with the background Rydberg-excited clusters [3]. However, the above scheme leads to an isotropic, non-directional emission of accelerated neutral atoms with modest currents. Here, we demonstrate an analogous neutral-acceleration scheme in laser-solid interactions, in which the positive ions are accelerated by the target normal sheath acceleration (TNSA). We report a copious emission (10^{11} per laser shot) of directed (along the target normal) beam of MeV neutral atoms, with almost 90% ion-to-neutral conversion efficiency, which has potential applications in tokamaks as injectors, high-finesse lithography, space physics and warm dense matter. The neutral flux as well as the conversion efficiency has been observed to increase with defocused laser illumination.

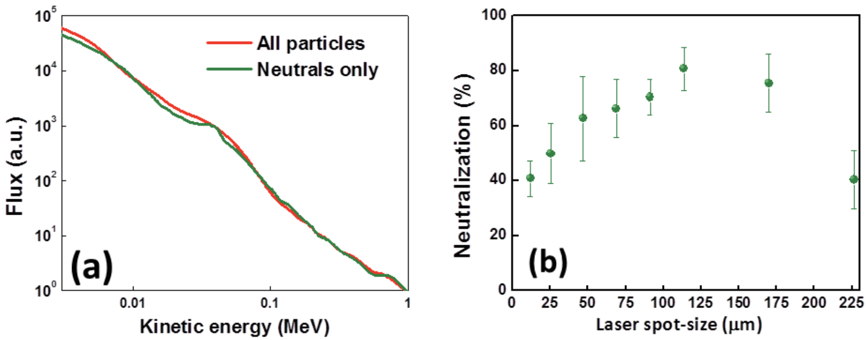

Figure 1: (a) Kinetic energy spectra of all particles and the neutrals. (b) Percentage of neutralization with defocussing.

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P.Th_48

Efficient neuron generation from solid-nanoparticle explosions driven by DPSSL-pumped high-repetition rate femtosecond laser pulse

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Recent developments of high-intensity laser enable us to evolve a new type neutron source. A number of experiments [1-5] demonstrated the possibility of laser-driven fusion using pure D_2 or CD_4 clusters. In these works, multi-keV deuterium ions were generated by Coulomb explosion of a few nanometres clusters. Since the cross-section of deuterium-deuterium (DD) reaction reaches its maximum at 1.75 MeV with center-of-mass system, much higher ion energy is required for efficient neutron generation. Features of the Coulomb explosion are that ion energy distribution function is proportional to the square root of its energy and the maximum energy is proportional to its radius [6]. Larger particles result in higher ion energy, although an intense laser irradiation is required for expelling electrons from the larger particles. We fabricated the solid deuterated-polystyrene (CD) nanoparicles of relatively large size to obtain high ion energy of ~1 MeV. The average size can be controlled with high precision between 100-700 nm (See Fig.1(a)). Efficient and stable neutron generation was obtained by irradiating an intense femtosecond laser pulse of $>5\times10^{18}$ W/cm^2. A yield of $\sim10^5$ neutrons per shot was stably observed (See Fig.1(b)) during 0.1-1 Hz continuous operation.

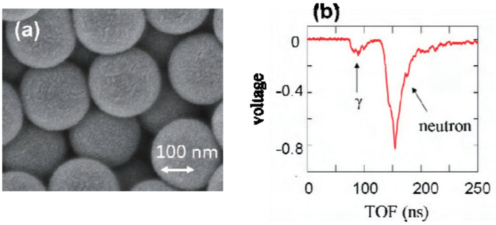

Figure1:(a)SEM image of CD nanoparticles. (b)Single shot neutron TOF signal.

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P.Th_49

DPSSL pumped 20-TW Ti:sapphire laser system for DD fusion experiment

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A diode-pumped solid-state laser (DPSSL) pumped 20-TW output Ti:sapphire laser system has been developed. A diode-pumped Nd:glass laser with output energy of 12.7 J in 527 nm was used as a pump source for a 20-TW Ti:sapphire amplifier. A $CeLiB_6O_{10}$ nonlinear optical crystal was used as a frequency doubler of the Nd:glass DPSSL[1]. Figure 1 shows typical output pulse energy of the 20-TW amplifier as a function of pumping energy and a near field pattern. A 1.65 J pulse energy was obtained by 4.5 J pump energy. The amplified seed pulse is compressed to typically 60 fs as shown in Fig. 1 by a vacuumed pulse compressor with 80% of transmissivity. Encircled energy ratio, into a circled with 8 μm diameter area, of far field pattern focused by off-axis parabolic mirror with F# of 3 is numerically evaluated to 40% at TW class output condition. Then focal intensity would reach to 10^{18}W/cm^2.

This all-DPSSL system contributes for stable and continual investigation of laser induced plasma experiment. We have succeeded continual and high efficient generation of DD fusion neutron from CD nano-particles by cluster fusion scheme using the 20-TW laser. A yield of ~10^5 neutrons per shot was stably observed during continuous 100 shots with repetition rate of 0.1Hz.

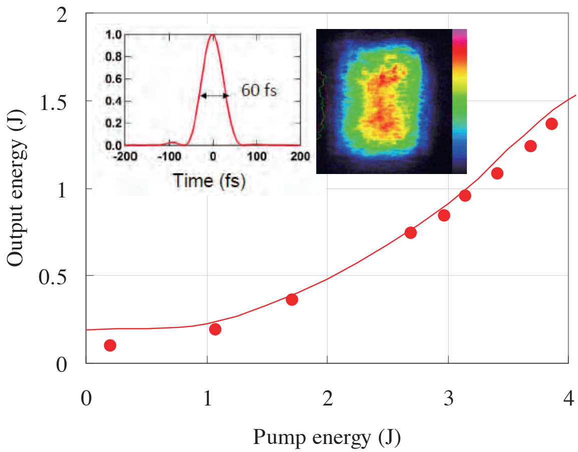

Figure 1: Typical output energy as a function of pumping energy and a near field pattern and pulse duration of the 20-TW laser.

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Characteristics of X-rays produced via laser Compton scattering using quasi-monoenergetic electron beam driven by laser-plasma acceleration

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In laser-plasma acceleration (LPA), a femtosecond electron pulse can be produced, because the wavelength of the accelerating field, that is the plasma wavelength, is the order of 10 μm. A compact electron accelerator will be realized using the extremely high accelerating field of more than 100 GV/m. The unique characteristics of LPA enable us to produce compact, all-optical, ultrashort X-ray sources. Such ultrashort X-ray sources have attracted much attention, because of their potential applications in investigating the ultrafast structural dynamics of materials through time-resolved X-ray diffraction and spectroscopy. The generation of ultrashort X-ray pulses using an electron beam driven by LPA has been conducted. One type of such X-ray sources is a laser Compton scattering (LCS) X-ray source, which is produced by scattering a femtosecond laser pulse off a femtosecond high-energy electron pulse. In this paper, we report the demonstration of X-rays produced via LCS using a quasi-monoenergetic electron beam with a narrow energy spread driven by LPA.

X-rays were produced by scattering a femtosecond laser pulse (800 nm, 140 mJ, 100 fs) off a quasi-monoenergetic electron beam containing 70 pC electrons in the monoenergetic peak with an energy of 60 MeV produced by focusing an intense laser pulse (800 nm, 700 mJ, 40 fs) on a helium gas jet. A well-collimated X-ray beam with a divergence angle of approximately 5 mrad was produced. The number of X-ray photons was estimated to be $2x10^7$ per pulse.

The characteristics of X-rays were also investigated using a numerical simulation. The spectrum of X-rays emitted within the scattered angle of 5 mrad had a quasi-monochromatic structure with a peak at 60 keV. The number of X-ray photons was $1.8x10^7$, which was in a good agreement with the experimental result.

The allowance delay range between the two laser pulses for the X-ray generation was approximately 100 fs, and was nearly equal to the duration of the laser pulse scattered by the electron pulse. This suggests that the X-ray pulse duration was shorter than 100 fs.

P.Th_51

Shock Formation by Plasma Filament of Microwave Discharge under Atmospheric Pressure

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Shock wave propagation associating with a coherent-microwave discharge is used for a microwave-boosted rocket as low-cost novel launch system, and the strong shock wave is needed for achieving better thrust performance. In microwave-induced gas breakdown, filamentary structures which have discrete ionization front are formed at the order of atmospheric pressure unlike the case of laser-induced breakdown, and the discrete structures disappear at lower pressure as reported by past studies [1-3]. A generated impulse by the shock waves depends on the plasma structures of filamentary arrays, and the obtained thrust becomes smaller when the filamentary structures are not observed [3]. For obtaining continuous thrust even at high altitude using microwave rocket, it is necessary to improve the thrust efficiency at the lower pressure. To examine clear relationship between generated impulse and plasma structure and achieve better thrust performance using the microwave discharge, we simulate discharge process by intense microwave under the atmospheric and lower pressure using two dimensional PIC-MCC code including electron impact ionization.

When plane microwave is irradiated to an ionization spot at the atmospheric pressure, electron number density rapidly becomes larger and gets to critical density. The incident microwave is reflected and scattered at the discharged spot and a localized strong electric field is formed ahead of the initial ionization region. The strong field is discretely located at a quarter of microwave wavelength from the original spot, and a newly discharged spot is created through electron-impact ionization originating in background electrons at the strong field region. With the discrete ionization structure, microwave supported detonation (MSD) is formed, and then the shock wave is driven by the attached heating region corresponding to the ionization front. On the other hand, new ionization spot is not generated at the lower pressure because the initial plasma rapidly diffuses before the electron number density reaches the critical density. The shock wave goes ahead of the heating region in the case of diffusive discharge process, and shock strength becomes weaker than the MSD mode.

For obtaining a strong shock wave under the lower pressure, a strong magnetic field is provided to induce electron cyclotron resonance (ECR) with the incident microwave. The number density at the original spot exceeds the critical density due to the ECR, and the microwave reflection forms the strong field region in front of the discharged spot. The filamentary arrays are obtained regardless of the lower pressure. We will discuss that the filamentary structure caused by the ECR may provide a strong shock wave at the lower pressure in the full paper.

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P.Th_52

Ion Interactions in Warm Dense Matter

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The physical processes involved in the interaction of ion beams in warm dense matter (WDM) (i.e. 1 - 100 eV, 0.01-100 g/cc) is fundamental to the understanding of condensed matter, solid-state physics, fusion sciences, and astrophysical phenomena[1]. In the WDM regime, the stopping power of particles differs significantly from that of both cold matter and ideal plasma due to free electron contributions, plasma correlation effects and electron degeneracy [2-4]. The creation a WDM state with a temporal duration consistent with the particles used to probe it has been extremely difficult to achieve experimentally. Advantageously, the short-pulse laser platform allows the potential to produce WDM [5,6] along with relatively short bunches of protons compatible of such measurements [7], however, until recently, the intrinsic broadband proton spectrum was not well suited to investigate the stopping power directly. This difficulty has been overcome using a novel magnetic particle selector, and the generation of picosecond bunches of monenergetic ($\Delta E/E$= 10%) protons (in the range 100-1000 keV) is demonstrated using the ELFIE laser at the Laboratoire pour l'Utilisation des Lasers Intenses (LULI). These protons bunches are used to probe high-density (5×10^{20} cm-3) gases (Hydrogen) that are heated by nanosecond laser pulses to reach estimated temperatures above 100 eV. Measurement of the proton energy loss within the material compared to the measured medium density profile allows the stopping power to be determined quantitatively. The experimental results in cold matter are compared to preexisting models to give credibility to the measurement technique. The results from heated matter show that the stopping power of 450 keV protons is dramatically reduced within heated hydrogen plasma.

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P.Th_53

THEORETICAL AND EXPERIMENTAL STUDIES OF THE ION FLUX INTERACTIONS WITH POROUS TARGETS

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VNIIEF has been studying, both theoretically and experimentally, the processes taking place under the effect of high ion fluxes on porous structures of different compositions, shapes, and sizes (from microstructures to nanostructures).

One of the examples of porous structures is thin mylar films with apertures made by low-energy ion fluxes. VNIIEF organized and conducted a series of experiments on accelerator EGP-10 and alpha-source to study the spectral distribution of ions after they had passed through thin (5 to 20 μm) films of different porosity ratios with pore sizes not larger than 1 μm.

A computational model was developed and used for the numerical simulation of the spectral distribution of ion fluxes passing through porous targets of different structures.

The report presents the obtained results of such studies.

P.Th_54

Hydrogen retention in plasma facing materials: The influence of the material microsturcture

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The development of new materials able to resist in the hostile environment of a fusion reactor is one of the challenges in the design of the future nuclear power plant. Tungsten is proposed as plasma facing material (PFM) in future fusion reactors [1–3] due their properties: high melting point and thermal conductivity, low sputtering yield, low thermal expansion, low activation rate and low tritium retention. However, some limitations have been identified that have to be defeated in order to fulfill specifications. In the case of laser fusion with direct target (e.g., HiPER project), light species (mainly H, D, T and He) which result from the target explosion, are implanted in W notably degrading its properties and leading to swelling, pore formation, surface exfoliation as well as, embrittlement beyond certain dose threshold [4,5].

In this work we focus on the study of H depth profiling in Nanostructured W (NW) coatings as compared to the massive W (from now on MW). For this purpose resonant nuclear reaction (RNRA) experiments are carried out in NW and MW samples implanted with (i) H at an energy of 170 keV, (ii) sequentially implanted with C (665 keV) and H (170 keV) and co-implanted with C (665 keV) and H (170 keV). Implantations were carried out at a fluence of $5x10^{16}$ cm^{-2} and at two different temperatures RT and 400ºC. RNRA data evidence that the H concentration for samples implanted only with H is higher for NW than for MW, and it becomes comparable for both kind of samples after sequential implantation with C and H. Increasing the temperature during irradiation up to 400ºC leads H to completely release for NW as well as, for MW samples.

The role of microstructure, radiation-induced damage and synergetic effects on light species behavior will be discussed.

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P.Th_55

NUMERICAL STUDIES OF A POSSIBILITY TO INCREASE TEMPERATURE OF X-RAYS IN ICF TARGETS

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The paper presents results of numerically studying the generation in a target of the field of X-rays of effective temperature above 300 eV (which is a typical temperature of the X-ray field in targets tested on NIF facility). The X-ray field parameters were studied using a flux of heavy ions and laser radiation (LR) of a shorter wavelength. Such LR of a shorter wavelength allows significantly increasing the limit intensity of the LR flux in targets and, thereby, increasing the effective temperature of X-rays up to 350 eV and higher.

Estimated parameters for the heavy ion and laser drivers are presented. These parameters will provide necessary conditions for the initiation of thermonuclear reaction.

P.Th_56

Experimental study of radiation temperature for gold hohlraum on SG-III prototype laser facility

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Hohlraum radiation temperature is an important foundation for inertial confinement fusion (ICF) research. Experimental measurements of radiation temperature by a streaked optical pyrometer and a soft x-ray spectrometer with 15 absolutely calibrated channels viewing through the laser entrance hole are performed on SG-III prototype laser facility，which shows that the results of the two methods agrees with each other well. The scaling of the hohlraum radiation temperature as a function of laser parameter, hohlraum size, and x-ray conversion efficiency is obtained. Maximum radiation temperature is found to be 230eV for 1.0mm diameter hohlraum with 8TW of 351nm light in a 1ns square laser pulse. Using the power balance relation, the laser-hohlraum coupling is deduced to be about 70%. The experiment shows that relative uncertainty of the measurement of the radiation temperature could be controlled within 3% under current conditions after precise calibration.

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P.Th_57

Characterization of halfraum as radiation sources for high-energy-density physics and inertial confinement fusion experiments

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Hohlraum/Halfraum is used as intensive x-ray source for various high-energy-density physics (HEDP) and inertial confinement fusion(ICF) experiments. Experiments that study radiation transport, equation of state, opacity and radiation hydrodynamics etc. are carried out in Shenguang III prototype laser facility, China. 8 beams of 3ω (351nm in wavelength) laser pulses with pulse-width 1 to 3ns inject axisymmetrically into the laser entrance hole of a halfraum and strike its golden wall which converts the laser energy into intensive x-ray. The experiment package such as cylinders filled with low density optically thin or optically thick foam, foils or steps etc. is attached onto the bottom of the halfraum and use the x-ray radiation as drive. In order to correctly interpret the experimental results, it is of great importance to obtain a clear understanding of the radiation environment generated using halfraums.

Experiments that characterize the halfraum radiation source are carried out along with the HEDP shots or independently. A novel x-ray diode array is used to measure the radiation fluxes from different directions. The x-ray diode use specially designed filter and diode to make an approximately flat spectral response in the photon energy range 100eV to 5keV[1], and the radiation flux is recovered with a weighted method which improves its recovery[2]. It is found that the angular radiation distribution has low fluxes at small angles(i.e. direction close to the halfraum axis) rather than a cosine distribution which has the maximum intensity at small angles. A multi-channel soft-x-ray spectrometer is used to recover the equivalent radiation temperature history and temporal evolution of the radiation spectrum. The unfolding techniques used to recovery the soft-x-ray spectrum include iterative methods using histograms or splines as base functions. The equivalent radiation temperature achieved is about 200eV to 250eV with a uncertainty about 3% which is obtained using uncertainty analysis based on Monte Carlo sampling. The temporal and spatial resolved plasma movement within the halfraum is measured with a streak camera. And the collision position of the expanding wall plasma is recovered with a time-integrated image from a pin-hole camera. The time-integrated radiation spectrum with higher spatial resolution is obtained with a transmission grating spectrometer. A view factor code is used to analyze the radiation distribution of the halfraum wall and the fields of view of these spectrometers.

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P.Th_58

Analytical model of multi-keV K-shell x-rays emission generated by nanosecond laser pulse irradiated solid target

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Multi-keV x-ray sources are widely used in experiments of inertial confinement fusion and high energy density physics such as backlit implosion, hydrodynamic instability, and equation of state. In conventional scheme, multi-keV x-rays are generated in hot underdense coronal plasma of nanosecond laser pulse irradiated solid target. The laser and target parameters including laser intensity, laser wavelength, laser focus spot size, laser pulse duration, and atomic number of target etc, which control the condition of the coronal plasma, can sensitively change the x-rays emission. An analytical model was developed to descript the multi-keV K-shell x-rays emission generated by nanosecond laser pulse irradiated thick solid target with Z=19~36. The emission volume which depends on the two-dimension temporal evolution of hot underdense plasma and the emissivity of x-rays which determined by electron temperature were considered using the analytical models for laser-driven ablation and x-rays emission. The temporal profile of x-ray power and the conversion efficiency of x-ray sources given by the analytical model are in reasonable agreement with the experimental results.

P.Th_59

Study of He-α source from Ti plasma with 10J-scale laser system[1]

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The characteristics of He-α lines from titanium plasmas are investigated with a small Nd:YAG laser facility, whose maximum output energy is about 12 J with pulse duration of about 10 ns at the wavelength of 1064 nm. The x-rays are detected with a x-ray photon counting charge-coupled device (CCD), which is carefully calibrated by a ^{55}Fe source, and a computer program is developed for analyzing the split pixel events [1]. The dependence of the He-α x-ray production on the focusing status is studied in great detail. The experimental result shows that the x-ray conversion efficiency can reach up to 10^{-5} at the laser intensity of 5×10^{13} W/cm^2, and the absolute x-ray yield around 4.7 keV is about 10^{10} photons per laser shot. This quasi-monochromatic He-α source could be used for the x-ray phase-contrast imaging [2].

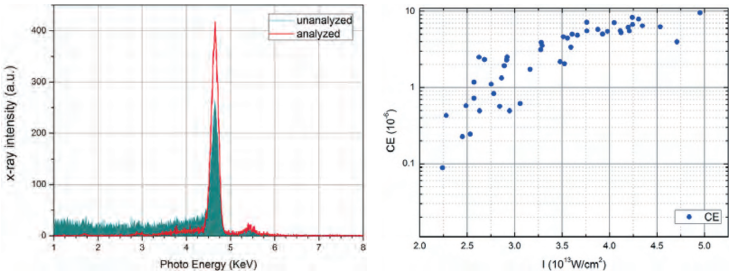

Figure 1: left) the spectrum of the He-α x-ray from a titanium plasma; right) the x-ray conversion efficiency in 4.7 keV versus the laser intensity.

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[1] This work is support by the National Natural Science Foundation of China (Nos. 11105147 and 11175197) and the Innovative Project of CAS (Grant No. KJCX2-YW-N36).

P.Th_60

XFEL resonant photo-pumping of dense plasmas and dynamic evolution of autoionizing core hole states

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As it has been the case for LIF (Laser-Induced Fluorescence) an equally revolutionary impact to science is expected for resonant X-ray photo-pumping. It will particularly allow outstanding steps forward in high energy density science: pumped cores hole states create X-ray transitions that can escape dense matter on a 10 fs-time scale without essential photo-absorption [1] to study matter under extreme conditions. In a proof of principle experiment at the X-ray Free Electron Laser LCLS at SCLAC we have successfully pumped inner-shell X-ray transitions in dense plasmas. Plasma creation was done with a YAG laser (λ=800 nm, E=24 mJ, τ=120 ps, ϕ=60 μm) irradiating solid aluminum that was mounted on a rotating cylinder (to provide fresh target surfaces for each shot, repetition frequency of 120 Hz). Parallel to the optical laser beam, the XFEL (10^{13} photons/shot, pulse duration 250 fs) was focused (20 μm) into the plume at different delay times and pump energies. Pumped X-ray transitions have been observed with a Bragg crystal coupled to a Princeton CCD with 2048x2048 pixels. A spherically bent mica Bragg crystal was employed in 2nd order reflection to simultaneously achieve extremely high spectral ($\lambda/\delta\lambda \approx$ 5000) and spatial resolution ($\delta x \approx$70 μm) while maintaining high luminosity and a large spectral range (6.90 - 8.35 Å).

We will present the first simulations carried out with the MARIA-code [1] that invoke LSJ-split atomic structure to interpret the XFEL driven X-ray emission from autoionizing core hole states. We also demonstrate that X-ray pumping allowed following the dynamic evolution of states and atomic populations in dense matter that could not be observed otherwise. Finally will discuss possible verifications of various atomic physics models in high energy density science.

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P.Th_61

ICF science study at the European XFEL, HED instrument

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Operational free-electron laser facilities with FLASH, LCLS, FERMI and SACLA provide the photon energy range from UV to hard x-rays, and have provided significant scientific outcome in the recent years. The European XFEL will start user operation in 2016 with photon energies of up to 25 keV, a photon flux in the order of 10^{12} photons/pulse and a pulse duration of 2 – 100 fs. Such parameters are particularly suited for the investigation of transitional processes during strong excitation inside solids or high-density plasmas.

The high-energy-density (HED) instrument [1] is one of the six baseline instruments at the European XFEL and now entered its technical design phase. Coupling with high-intensity (>100 TW) and high-energy (>100J, few ns) laser systems with relatively high repetition rate (1 – 10 Hz), it will provide outstanding research opportunities to elucidate physics related to strongly-excited solids, high-pressure science, warm-to-hot dense matter, relativistic plasma physics and high-field science [2].

In this presentation, currently foreseen x-ray techniques and prototypical experiments proposed at the HED instrument will be discussed. Among other applications, the presentation will concentrate on fusion-related issues, particularly on fast electron beam transport and on warm dense matter physics. The unique experimental platform will help to unravel the complex femto- to pico-second dynamics of equilibration, extreme current transport and electromagnetic fields.

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[2] European XFEL User Consortium for HIBEF.   http://www.hzdr.de/hgfbeamline

P.Th_62

Punch-out of gadolinium targets by laser pulse for laser-produced Beyound-EUV light source

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In the recent years, several efforts [1-3] have been devoted to the development of a beyond-extreme ultraviolet (BEUV: λ = 6.7nm) light source for the future lithography, which is a key technology for the mass production of semiconductor devices. A high-power, debris-free, and high repetition-rate BEUV light sources must be developed for a practical lithography system. Laser-produced gadolinium plasma is expected to be an efficient BEUV light source owing to is compactness and high conversion efficiency from the incident laser energy to the BEUV light energy. One of the ways to realize the practical BEUV light source is to use a minimum-mass target, which contains the minimum number of target atoms required for BEUV radiant energy. Although the droplet scheme has been demonstrated to supply the minimum-mass tin target for 13.5 nm EUV light source generation, it is difficult to supply gadolinium target as droplet targets because the melting temperature of gadolinium (1585K) is much higher than that of tin (505K). A punch-out scheme is proposed as alternative technique of supplying the minimum mass gadolinium target at a high repetition rate. A thin gadolinium layer coated on a substrate is used in the punch-out scheme. The substrate is transparent for laser light, and a punch-out laser irradiates the gadolinium layer though the transparent substrate to push only the gadolinium layer. Then the flying gadolinium target is heated with another laser to produce BEUV light source plasmas. In this study, fine structure of the punch-out gadolinium target was measured with laser shadowgraph. Fragments of gadolinium were found in the punched-out target pushed by non-uniform laser beam. Jet-like structure was found in the case that gadolinium target was pushed by homogenized uniform beam. 100 m/s of flying velocity of was obtained with 10^{10} W/cm^2 of intensity of the punch-out laser. The punch-out scheme can be used to supply target at 10kHz repetition-rate.

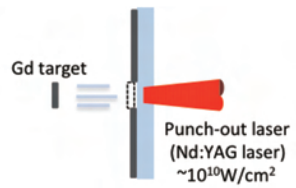

Fig1: Schematic illustration of punch-out

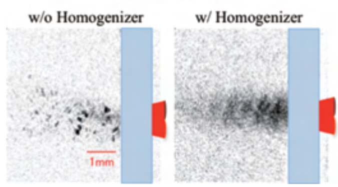

Figure 2: Shadowgraph images of punch-out

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P.Th_63

Dependence of Conversion Efficiency of 6.X nm Beyond-Extreme Ultraviolet Light on Wavelength of Drive Laser

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Continuous development of semiconductor device technologies gives large impacts in our society. Photolithography is a key technology for volume manufacture of higher performance and more compact semiconductor devices those are required. Smaller and more complex structures in the device can be fabricated by shortening light wavelength of the lithography. Extreme ultraviolet (EUV) light, whose wavelength is 13.5 nm, is a promising candidate for the next generation lithography. Development of Beyond-EUV (B-EUV) light, whose wavelength is 6.X nm, is started to extend the capability of the EUV lithography. One of the most important issues in this development is to increase conversion efficiency (CE) from laser energy to B-EUV light energy. Gadolinium plasmas generated by a Q-switched Nd:YAG laser were studied as a B-EUV light source in this research. Wavelength of the drive laser was switched from 1.06 to 0.53 μm to change electron density of laser-energy-deposition region. Radiant energy and B-EUV spectrum from laser-produced Gd plasmas were measured with transmission grating and grazing incidence spectrometers, respectively. Energy was defined as the ratio between radiant energy within 0.6% bandwidth at 6.7 nm and incident laser energy. This bandwidth is determined by a spectral reflectivity of multilayer mirrors used in the B-EUV lithography system. Figure 1 shows B-EUV spectra obtained by 1.06 or 0.53 μm laser irradiations. Out-band emission clearly increases in the case of the 0.53 μm irradiation compared to the 1.06 μm irradiation. Figure 2 shows dependence of CEs on laser intensities and wavelengths. Increment of out-band emission results in decreasing CEs as shown in Fig. 2, because more portion of laser energy is converted to the out-band emission. We will present the results obtained with longer wavelength laser irradiations.

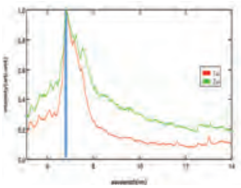

Fig.1: B-EUV spectra obtained by 1.06 or 0.53 μm laser irradiations

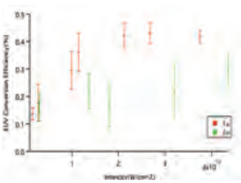

Fig.2: Dependence of CEs on laser intensities and wavelengths

References

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P.Th_64

Characteristics of extreme ultraviolet emission from high-*Z* plasmas

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Recently, the possibility of switching to an even shorter EUV wavelength of 6.*x* nm has been pointed out [1]. In fact, the 6.*x*-nm beyond EUV (BEUV) emission can be coupled with a Mo/B_4C or La/B_4C multilayer mirror whose reflectivity is currently 40% at 6.5-6.7 nm, (theoretical maximum >70%). The UTA emission exploited in Sn is scalable to shorter wavelengths, and Gd has a similar conversion efficiency to Sn, though at a higher plasma temperature, within a narrow spectral range centered near 6.7 nm.

We demonstrate the EUV and soft x-ray sources in the 2 to 7 nm spectral region related to the beyond EUV (BEUV) question at 6.x nm [1-7] and the water window source [8] based on laser-produced high-*Z* plasmas. Resonance emission from multiply charged ions merges to produce intense unresolved transition arrays (UTAs), extending below the carbon K edge (4.37 nm). An outline of a microscope design for single-shot live cell imaging is proposed based on high-*Z* plasma UTA source, coupled to multilayer mirror optics. We will discuss the value of *x* in 6.*x*-nm BEUV emission to optimize coupling with the recent multilayer mirror developed by FOM. In addition, and we will propose new scheme for a microscope in water window spectral region.

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P.Th_66

Optical properties of Neodymium-Doped Fluorides for the VUV devices

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Optical devices in short wavelength region are required for gamma ray detection, photolithography, and spectroscopy. Fluorides materials have a potential for short wavelength devises because of its wide band gap [1]. We investigated time-resolved photoluminescence spectra of Nd^{3+} doped LaF_3 and $LuLiF_4$ excited by plural light sources for development of vacuum ultraviolet (VUV) devices (Figure 1). For investigating effect of light sources, we used F2 laser, Ti:Sapphire laser and extreme-ultraviolet free-electron laser (EUV-FEL). EUV-FEL is the Spring-8 compact SASE source (SCSS) test accelerator in RIKEN and is a prototype accelerator of XFEL [2]. Time resolved photoluminescence spectra were obtained using a VUV streak camera system [3]. Nd^{3+}:LaF_3 has VUV emission at 172 nm while Nd^{3+} :$LuLiF_4$ emission was at 178 nm and 182 nm. In the case of EUV-FEL excitation, the temporal profile of these peaks was found to have a slow component, aside from the well-established fast component [4]. On the other hand, one decay component was observed under other light sources. This result shows difference in the excitation process.

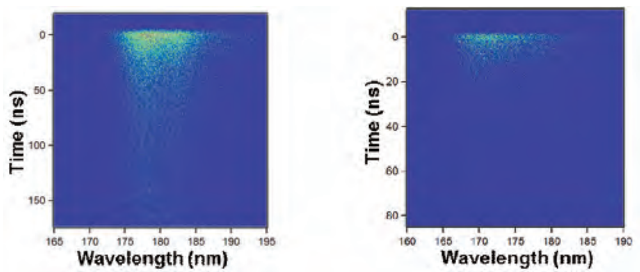

Figure 1: Streak camera image of fluorescence from Nd^{3+}:$LuLiF_4$ (left) and Nd^{3+}:LaF_3 (right) excited by EUV-FEL

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P.Th_67

ZnO scintillator with high spatial resolution for soft X-ray region

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ZnO crystals are studied for scintillation in short wavelength region. Previously, we have studied temporal property of fluoresce from ZnO using extreme ultraviolet or soft X-ray light source [1][2]. The important property of the scintillator is not only temporal resolution but also spatial resolution [3]. In this work, we evaluate the spatial resolution of ZnO scintillator as an imaging component in a high-spatial resolution in-situ imaging device for soft X-ray pulses.

The images of emission patterns from ZnO scintillator were observed by a single shot measurement with the soft X-ray laser excitation at Japan Atomic Energy Agency (JAEA). The excitation laser was focused to a spot size of 1 μm on the scintillator by a Fresnel Zone Plate (FZP). The FZP was shifted along the propagation direction of the soft X-ray beam for changing the focal spot size at the ZnO surface. Figure 1 shows the FZP-positions dependence of the focal spot size. The waist radii were 5.0 μm along the horizontal-axis and 4.7 μm along the vertical-axis. We also evaluated the spatial resolution of the magnifier, which consists of the Schwarzschild mirror, two lenses and camera lens to be about 5 μm. These results suggest that the ZnO scintillator has sub-micron spatial resolution taking into account the spatial resolution of a measuring assembly and can be applied to an in-situ imaging device for soft X-ray/X-ray sources.

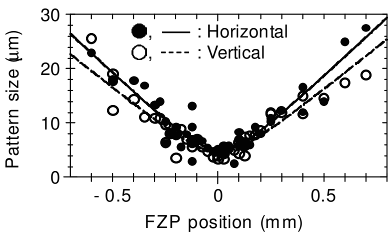

Figure 1: Half width at $1/e^2$ of the maximum of a Gaussian fit to the image of the ZnO emission pattern at different FZP positions.

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P.Th_68

VUV fluorescence from Nd- and Er-doped glass-scintillator

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Recently, scintillators and laser materials in the vacuum ultraviolet (VUV) region are explored for gamma-ray detection, spectroscopy, and photolithography. Rare earth-doped fluoride crystals have potential for scintillators or light-emitting device materials in VUV region and have been studied. The crystals have good quantum efficiency, although it is difficult to grow large and high-quality crystals in large quantities. On the other hand, glasses are more suitable for mass production and VUV fluorescent materials consisting of glasses are required. Previopusly, Pr-doped glass was reported to be a fast scintillator with a response time short enough to detect x-ray or neutron from the imploded core during inertial confinement fusion [1]. APLF glass has high transmittance in the short wavelength region, which is also a characteristic of wide bandgap fluoride crystals. Therefore, APLF glass is potentially a fast scintillator in the VUV region when doped with a rare earth ion. In this work, we report the development of Nd- and Er-doped APLF glass scintillators and their optical properties in the VUV region. VUV fluorescence from glass was observed with the third harmonics of Ti:sapphire laser (1 kHz, 290 nm, 200 fs) excitation. Figure 1 shows the photoluminescence spectrum obtained from streak image.

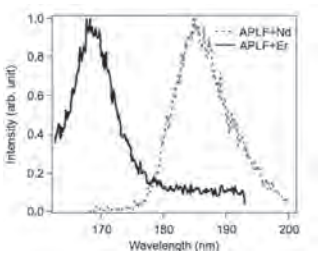

Figure 1: The photoluminescence spectrum from Nd- and Er-doped APLF glass scintillator.

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P.Th_69

A Single-shot Terahertz Time-domain Spectroscopy Instrument for Intense Laser System

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A single-shot terahertz time-domain spectroscopy method is developed using an echelon-pair [1]. Terahertz waveform is encoded to a beamlets array by electro-optic effect [2], with a total time window of 37.7 ps and a time step of 94.3 fs. Comparing with spectral encoding methods, this technique directly encodes terahertz waveform to spatial resolution, which is more suited as a terahertz diagnosis for high power ultra-short laser systems with inherent spectral fluctuations.

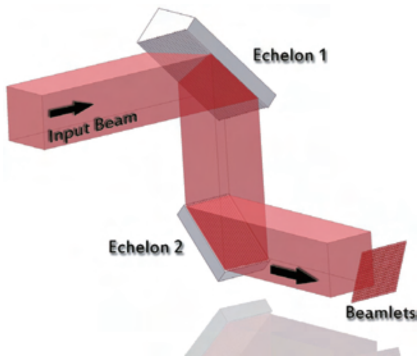

Figure 1: Schematic of reflective echelons pair.

With this scheme, we succeeded in the diagnosis of the THz wave generated by two-color laser ionized air-plasma with a 0.16 TW laser power and by laser-solid interaction with a high laser power of more than 20 TW inside vacuum system.

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P.Th_70

Probe beam-free Detection of Terahertz Wave by Electroluminescence induced by Intense THz Pulse

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Recently, MW THz pulse with an electric field higher than 100 kV/cm has been realized with a table-top short pulse laser system by several schemes including two-color laser generated plasma [1]. With those new sources, it is possible for the THz field to directly drive the electrons inside various materials. Such an effect has been observed so far through an enhancement of nitrogen fluorescence by the THz field in gas plasma [2] and luminescence with a low-temperature quantum wells semiconductor [3].

In this report, we introduce a direct THz electric field detection method by measuring the electroluminescence (EL) induced by intense THz pulse inside commonly available light emitting diode (LED). An intense THz wave as strong as ~0.8 MV/cm is obtained by the two-color scheme. It is focused onto the LED chip accompanied by an external DC voltage. The emitted luminescence collected by a gated intensified CCD camera is proportional to the incident THz field. The scheme can be useful to realize a low-cost, probe-free THz detection and imaging system.

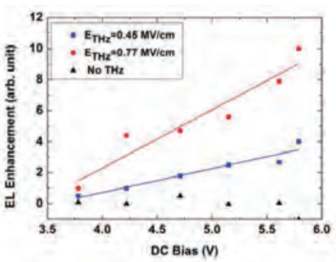

Figure 1: Enhancement of EL against the applied external DC bias for two different incident peak THz electric fields, compared to the case with no THz field.

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O.Th_A13

Magnetized Fast ignition (MFI) and Laser Plasma Interactions in Strong Magnetic Field

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The critical issue of the fast ignition has been recognized to be the coupling efficiency between a short pulse laser and a core plasma. In this issue, the ultra-intense laser plasma interaction (U-LPI) and the relativistic electron transport (RET) are the critical physics processes. In the U-LPI, the generated relativistic electron energy is required to be no more than 5MeV, and in the RET, the diameter of the heating area should be less than 100μm. In this paper, the effects of high external magnetic filed on the U-LPI are discussed.

The magnetic field higher than 6kT could be generated by compressing a few 100T imposed magnetic field by using imploding plasmas, In this case, the electron cyclotron frequency is higher than the 1μm laser frequency and a right handed circular component of the incident laser could penetrate into over-dense plasmas as whistler waves. This suggests that the laser energy is directly deposited in the over dense plasma and the average hot electron energy could be lowered. Therefore, the higher coupling efficiency is expected. The acceleration of electrons by the whistler waves is due to the cyclotron resonance: $\omega\text{-}kv_z\text{-}\omega_c/\gamma \cong 0$. In the high em field, the particle v_z and γ are oscillating through the phase trapping of electrons in the large amplitude wave. The electron momentum distribution in the 10kT B-field is compared with that in the zero magnetic field in the Fig.1. It is clarified that the momentum distributions are affected by the magnetic field. The appropriate irradiation and B-field conditions are under investigation for lowering the accelerated electron energy and the angular divergence. The further PIC simulation results and the analytical interpretations will be presented in the conference.

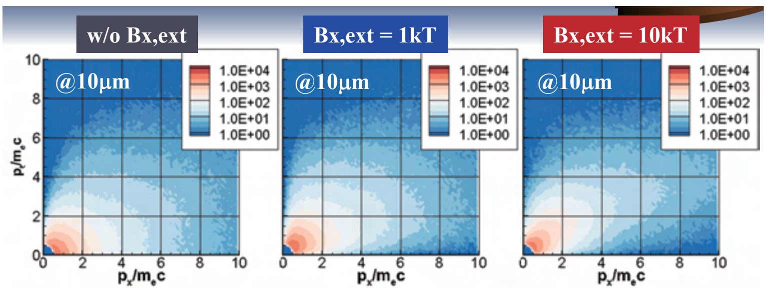

Fig.1 Longitudinal (P_x) and Transverse (P_t) distribution

Enhancement of fast electron energy deposition by external magnetic fields

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Recently, magnetic fields have been proposed for guiding and enhancing energy deposition of hot electrons in the compressed core of fast ignition targets [1]. B-fields of a few kTesla are required to guide hot electrons towards the dense fuel. Two approaches have been proposed so far for generating so strong magnetic fields: magnetic flux amplification [2] and field generation by laser-driven external coils [3]. In the first approach, it has been reported that, after the flux amplification, hot electrons are guided towards the dense core by an increasing magnetic field resulting in a significant 'backscattering' of those electrons due to the mirroring effect [1]. The second approach is based upon generating B-fields by a laser-driven external single-turn coil at a time close to the end of the target implosion and offers the possibility to generate the optimal field distribution for hot electron guiding. Here, the main issue is to ensure the magnetic field penetration up to the dense core over times of the order of one nanosecond [3].

A model for resistive diffusion and amplification of external magnetic fields has been developed. This model is based on the post-processing of the plasma evolution obtained from radiation-hydrodynamic codes. Its aim is to obtain the B-field distribution at the time of the peak ρR. Three target configurations have been studied: (i) the standard cone-target configuration, (ii) a new target design that consists of two opposed cones with the imploding shell inside them [4], and (iii) the target used in an integrated experiment carried out at ILE. Hot electron transport calculations have been performed by means of the 2D hybrid code PETRA [5]. Electron energy deposition in the compressed core with and without magnetic fields for the three targets mentioned will be compared. In addition, the ignition energies with and without external magnetic fields will be shown in order to assess the benefits of using those fields.

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O.Th_A15

Electron Beam Guiding by Strong Longitudinal Magnetic Field

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One of the most crucial issues of fast ignition is efficient core heating by laser produced fast electron beam. The main factors in preventing efficient heating are (1) too high fast electron energy and (2) too large beam divergence. The fast electron energy could be controlled by eliminating pre-plasma generation and by using heating laser with shorter wavelength. On the other hand, as for the beam divergence, it is difficult to control the angular spread of fast electrons since laser-plasma interactions are the non-linear phenomena. So there are some ideas on guiding of fast electron beam with large divergence angle using self-generated [1-3] or externally-applied magnetic fields [4]. In the present paper, on the basis of 2D PIC simulations, we evaluate the effects of externally-applied longitudinal fields on fast electron generation and propagation.

We evaluated the pitch angular distribution of fast electron energy just after generation under the external magnetic fields (Fig.1). Since the Larmor motion in the perpendicular direction is added during laser-plasma interactions, the pitch angle becomes larger for the case with the external fields, and then the beam energy contained within a certain angle becomes smaller. We also evaluated the spatial divergence of beam after propagation of a certain distance (Fig.2). Even if the fast electrons having large pitch angles, they are trapped by the magnetic fields and propagates along the magnetic field lines. As the result, the fast electron beam can be collimated by the external magnetic fields. It is found that the required magnetic field strength for beam collimation is B_{ext} > a few kT for the laser intensity with $I_L = 10^{18} \sim 10^{20}$W/cm^2. We will present these simulation results and discuss the more details in the conference.

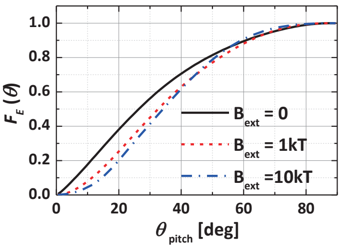

Fig.1 Pitch angle distribution of fast electron energy containing within pitch angle θ_{pitch} for $I_L = 10^{19}$W/cm^2.

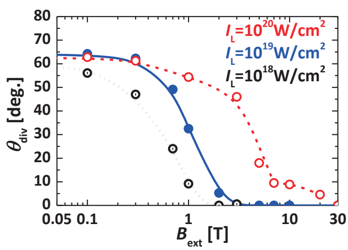

Fig.2 Spatial divergence after propagation of a certain distance for $I_L = 10^{18} \sim 10^{20}$W/cm^2.

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O.Th_A16

Compression of the Magnetic field in a Coned-guided Implosion

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In the Fast Ignition research, reduction of the divergence angle of heating electron beam is urgent issue. In the recent researches suggest that the magnetic field plays an important role in the problem, especially for the controlling of the high energy electron transport toward the compressed core plasma. At ILE, Osaka University, generation of a strong external magnetic field (~10kT) is demonstrated successfully using a laser-driven capacitor-coil target [1]. In such a strong magnetic field we cannot ignore the effect to the reduction of thermal conduction which is strongly related to implosion dynamics, as well as the effect to the hot electron transport. Therefore, magnetic field transport code must be solved with two-dimensional radiation hydrodynamic code simultaneously or strongly coupled with each other when we investigate the effect to the implosion dynamics. Especially, the high Hall parameter effect and the Nernst effect are our most interest.

In the preliminary research, we have developed a magnetic field transport code where temporal evolution equations of the magnetic field were solved as a post-process of 2-D radiation hydrodynamic simulation [3]. The results show that the magnetic field is generated by the $\nabla T_e \times \nabla n_e$ term, and is compressed by the implosion. In addition, we find that the magnetic field reaches 5 MG at maximum compression. This simulation code will be extended to simulate the transport of external magnetic field in axial direction. The electron beam reflection due to the mirroring effect in the strong magnetic field can be estimated. Also implosion dynamics and electron transport under such a strong magnetic field will be discussed. Finally, optimum applied magnetic field is proposed for the Fast Ignition.

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O.Th_B9

Laser driven ion acceleration experiments at RRCAT, India

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The acceleration of high energy ion beams up to several tens of MeV, following the interaction of intense ultra-short laser pulses with solids, has been an area of active research in the last decade [1]. The mechanisms leading to forward-accelerated, high brightness, short pulsed proton and heavy ion beams, operating at currently accessible intensities in laser matter interactions, are mainly associated with the large electric field set up by the laser-accelerated electrons at target interface (TNSA) [2]. Therefore, efficient laser energy coupling and understanding of the accelerating mechanisms is of profound importance for it potential applications.

In this report, we present, our initial experimental results on MeV ions generation by mildly relativistic (~10^{18} W-cm^{-2}) short-pulse (50 fs) laser interaction with solid targets of different thicknesses and multi-layers. The accelerated ion beam has been primarily characterized using a Thomson Parabola Ion Spectrograph (TPIS) equipped with a micro-channel (MCP) plate coupled with a 16 bit EMCCD camera placed along the target normal. Three Faraday Cups, placed at 10°, 15° and 25° with respect to the target normal, along with the MCP time of flight signal, provide the total ion flux and the angular distribution. The pre-pulse activity was monitored by recording the 2ω and 3/2ω in the specular direction. Our observed proton energies at these intensities are comparable to the ones expected from the known scaling laws for metal targets. Our initial experiments show a three-fold enhancement in proton energies from semiconductor targets compared to a metal target, under identical laser conditions. Further, an optimum pre-pulse intensity was found to help in generating high energy proton beam in the target forward direction. Details of experiments and our understanding on the results will be presented.

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O.Th_B10

New mechanisms for generating super-ponderomotive electrons in laser-irradiated targets

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Electron heating in laser-irradiated targets is crucial for production of energetic ions and for other applications, including x-ray generation, positron production, and fast ignition. Electron quiver energy in a laser beam is of the order of the ponderomotive potential, which is typically below the energy range of interest. This talk will present two new complementary collisionless mechanisms that enable production of super-ponderomotive electrons in laser-irradiated targets [1,2]. Both mechanisms rely on significant reduction of electron dephasing from the laser in an extended under-dense plasma. Such plasma is naturally formed in front of a target during the prepulse, and it can extend many wavelengths from the target surface along the beam path. Propagating through this plasma (preplasma), the main part of the laser beam creates a positively charged channel if the beam is significantly longer than the characteristic time of electron response. An electron accelerated by the laser performs betatron oscillations across the channel under the effect of the transverse electrostatic field while moving along with the beam. In the ultrarelativistic limit (a_0>>1), the betatron frequency is strongly modulated by the laser field. It has been previously overlooked that such modulation makes the oscillations parametrically unstable. The resulting amplification of the oscillations decreases electron dephasing from the laser and thereby significantly enhances the electron energy gain [1]. The dephasing can also be reduced by a quasi-static longitudinal electric field that naturally establishes at the entrance into the channel due to its coaxial structure. In this case, the axial acceleration is insignificant in terms of the direct energy gain in contrast with the wakefield acceleration. However, the reduction of the dephasing leads to a subsequent extended interaction with the laser field and results in a significant energy enhancement. The strongest increase in energy occurs if the interaction with the longitudinal field is terminated as the electron passes through a zero in the vector potential of the laser field. This mechanism is complementary to the mechanism of the parametric amplification of betatron oscillations if it precedes the latter, so that a combination of the two can produce super-ponderomotive electrons with energies exceeding what is predicted in [1] and [2] for each mechanism separately.

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O.Th_B11

Thin Cryogenic Hydrogen Targets for Laser and Particle Beams

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Target composition and geometry play a crucial role in laser-plasma interaction experiments. With the recent availability of large temporal contrast ratios at high power laser facilities the use of ever thinner targets becomes desirable. Simulations of new laser driven particle acceleration regimes exploiting these targets (e.g., radiation pressure acceleration (RPA) [1] and laser breakout afterburner (BOA) [2]) predict particle energies in the GeV range in contrast to tens of MeV achievable in present target normal sheath acceleration (TNSA) experiments.

In this contribution we will present our efforts to produce micrometer-sized cryogenic targets from pure hydrogen in foil-like geometry as well as polymer films with thicknesses of some hundred nanometers. While cryogenic hydrogen targets serve as pure proton sources and thus could provide very high proton energies, polymer targets with a carbon to hydrogen content ratio of 1:2 still provide high proton energies while being beneficial in terms of handling. According to particle in cell code (PIC) simulations both types of targets are expected to deliver laser driven particles with several hundred MeV per nucleon. Possible applications of these high energy particle beams include proton driven fast ignition [3] and the production of secondary particle beams such as neutrons [4]. Cryogenic hydrogen targets could also be used in high energy density experiments with swift ions produced by either lasers or conventional accelerators [5].

We will give an overview of target production and characterization at the Technische Universität Darmstadt as well as preliminary and planned experiments at the PHELIX laser facility at the GSI Helmholtzzentrum für Schwerionenforschung GmbH. The project is supported by the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany and the European High Power Laser Energy Research (HiPER) project.

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O.Th_B12

Laser ion acceleration with low density targets: a new path towards high intensity, high energy and high current ion beams

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Intense research is being conducted on sources of laser-accelerated ions and their applications, motivated by the exceptional properties of these beams: high brightness, high spectral cut-off, high directionality, laminarity, and short duration (~ps at the source). It was recently shown experimentally that a promising way to accelerate ions to higher energies and in a collimated beam is to use under-dense or near-critical density targets instead of solid ones. In this case, volume effects dominate, enhancing the laser-to-proton energy conversion, and allowing to reach high ion energies with a high number of accelerated ions. This scheme also leads to less debris than solid foils and is adapted to high repetition lasers. Under certain conditions, the most energetic protons are predicted to be accelerated by a collisionless shock mechanism that significantly increases their maximum energy.

The transition between various laser ion acceleration regimes depending on the density gradient length (controlled by the delay between the lasers) was studied at LULI in May 2011 using a two-laser setup. A first ns pulse was focused on a thin target to explode it and a second laser (350 fs pulse duration, high intensity) was focused on the exploded foil. Protons with energies close to the ones reached using solid targets were obtained for various exploded foil configurations with ~5 J of laser energy. As this regime scales well with laser energy, new experiments were performed in 2012 with more laser energy (~180 J) on the LLNL Titan laser with a similar setup. In this high energy regime, protons with energies significantly higher than the ones reached for solid targets were obtained while keeping a good beam quality. These results demonstrate that low-density targets are a promising candidate for an efficient compact proton source. This source can be optimized by choosing appropriate plasma conditions.

O.Th_C9

Conceptual Design of Laser Fusion Experimental Reactor (LIFT) Based on Fast Ignition Scheme

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In 2012, we organized a design committee for a laser fusion experimental reactor to clarify critical issues in demonstrating electric power generation by laser fusion. The committee consists of a supervisor team, a simulation and theory for core plasma team, a laser team, a fueling team and a chamber and system team. Fifty-one members including researchers from universities and companies were engaged in this activity. We are now preparing an interim report to fix consistent system parameters.

Our plan for the experimental reactor is divided into 3 phases. The mission of the phase I is to demonstrate repetitive fusion burns in a burst mode. The repetition rate is 1Hz and the total shots number in one burst is 100. The chamber is a simple vacuum vessel without a blanket and the cooling system. The operation will be stopped when the average temperature of the chamber exceeds 200 ^{o}C.

The mission of the phase II is to show the production of electric power. The operation will be continued for a couple of days at 1 Hz. The chamber is a dry wall chamber with solid blanket. Although the final goal is a wet-wall chamber with liquid LiPb blanket, the dry wall was chosen to shorten the time for power generation. The heat cycle has a tritium recovery system but reuse of the tritium during operation is optional. After demonstration of electric power generation, development of liquid wall chamber will be started. Liquid wall is the key scheme to realize a commercial power plant. Technical issues related to the liquid first wall and the liquid blanket will be tested in this phase.

The mission of phase III is to clarify reliability and economics of the liquid wall chamber. Tritium breeding and material test will be also included in the mission. The chamber is a small prototype of KOYO-F that is a commercial power plant based on the fast ignition [1]. All equipment necessary for a fusion plant will be installed to this system. The final goal of this system is continuous operation close to one year and production of tritium necessary to start a demo plant.

The laser system is a Laser-diode-pumped, cooled Yb:YAG ceramic-laser whose output power is 400 to 600kJ for compression beams and 200kJ for the ignition beam. This laser system will be used commonly in all phases.

The critical issue in each step will be reported at the conference.

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O.Th_C10

Release of Real Size, Fast Ignition Target from Sabot

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In the case of fast ignition, laser fusion power plant KOYO-F, targets will be injected into the chamber at the velocity of 100 m/s and the repetition rate of 4Hz[1]. Since the ignition laser irradiates the compressed core through the guide cone, the target must face to the beam with accuracy of +/- 2 degree to avoid conflict of laser beam with the guide cone. The injector consists of a gas gun followed by a velocity detection section, a coil gun section for fine velocity adjustment, a sabot release section, and a tracking section. The target will be mounted on an aluminum sabot and accelerated to 90 +/- 5 m/s with a gas gun and the velocity will be controlled to 100+/- 1 m/s with the coil gun. The required velocity will be easily realized with a gas gun but experimental demonstration is necessary to discuss the pointing and tumbling of target after release of the sabot since they strongly depends on the fabrication accuracy of the system.

We built a single-shot, gas gun with a sabot release section to discuss the stability of a dummy target after release. Figure 1 (a) shows a schematic diagram of the system. Current achievements are 80+/-5m/s in the velocity, +/-0.6 mrad in the pointing, 1+/-1.7rad/s in the tumbling. We found the tumbling is the critical issue toward the goal.

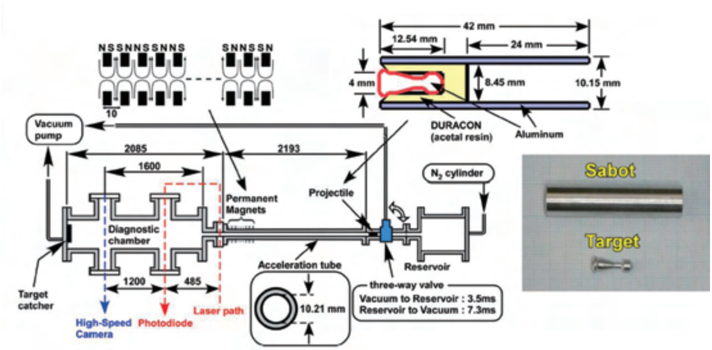

Fig. 1 Gas gun and sabot separation unit to discuss the stability of fast ignition target.

O.Th_C11

Development of Position Measurement Unit for Flying IFE Target

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Present status of the development of the position measurement unit for injected IFE target is reported. The injection and tracking demonstration system is under construction at Osaka University. The position measurement unit (PMU) is one of the most important units in the tracking system. The PMU uses Arago spot [1~3]. Figure 1 shows the concept of the PMU. The PMU are set along the target injected path. Flying injected IFE target is irradiated by the orthogonal pulsed laser beam. Laser irradiation time, T, is measured by the photo sensor with timer. The 2D Arago spot image is compressed into the 1D image by the cylindrical lens for reduction of the data size [4]. The 1D image is recorded by the linear CMOS sensor.

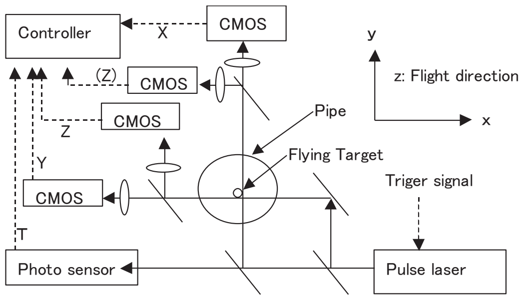

Figure 1: Position Measurement Unit.

Light intensity distribution data of 1D image on the linear CMOS sensor is transferred to the controller. The local position of the IFE target in the PMU, (x, y, z), are calculated in the controller. The arrival time and the arrival position of the IFE target at the reactor center are calculated using the data (T, x, y, z) of the PMU.

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O.Th_C12

Performance of the new apparatus for fuel layering demonstration of FIREX targets

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The fuel layering for Fast Ignition Realization EXperiment (FIREX) targets has been studied under the collaboration between the Institute of Laser Engineering (ILE), Osaka University and the National Institute for Fusion Science (NIFS). The target consists of a 500 μm plastic shell, a gold cone guide and a glass fill tube. The final goal is to create a solid DT or D_2 fuel layer with ~20 μm in thickness on the inner surface of the plastic shell. We have two layering strategies: foam shell and cone guide laser heating methods. To date, less void fraction of solid H_2 within a foam layer has been realized for the former method [1], and a preliminary demonstration to create a thin H_2 ice layer on the inner surface of a 2 mm Polystyrene (PS) shell has been succeeded by the later method [2]. Our study has reached the detailed optical observation stage. Therefore, a new apparatus designed for optical observations with an easy target exchange mechanism has been built. Active vibration isolators are equipped to prevent the vibration from a cryocooler, and glass windows with wide aperture are installed for direct observation of a microscope. Fig. 1 shows the target exchange mechanism. Metal seal has proven to use several times under cryogenic environment without replacing. In this paper, the performance of the new apparatus is described.

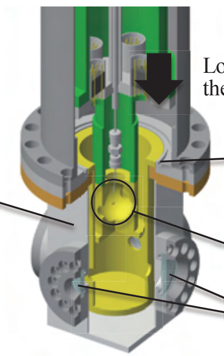

Figure 1: Target exchange mechanism of the new apparatus.

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