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K.Mo_A1

Fusion Energy Research in Japan’s Nuclear Energy R&D Program

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JAEC has been promoting nuclear energy R&D activities, recognizing that nuclear power will continue to be a stable base-load source of electricity if its sustainability is progressively improved, as it can contribute to energy security, reduce the impact of volatile fossil fuels prices and mitigate the effects of climate change in an era of increasing global energy demands. The objective of the short-term R&D activities is to utilize existing assets as effectively as possible and that of the mid-term R&D activities is to prepare technologies that should be introduced in due time for assuring the high sustainability of nuclear fission energy technology. The objective of the long-term R&D activities is, on the other hand, to explore radically new nuclear energy technologies and much of the activities in this category are devoted to nuclear fusion R&D.

The objectives of the current nuclear fusion R&D activities are 1) construct ITER, 2) establish the basis for the development of tokamak demonstration power plant through advanced fusion plasma research utilizing JT-60SA and development of the neutron-resistant materials and an intense neutron source required for this activity, engaging in an engineering validation and design activity (EVEDA) for the IFMIF, 3) explore alternatives to tokamaks, such as the heliotron line and inertial fusion lines. As for inertial fusion approach, currently experimental progress has been focused on fast ignition by performing integrated experiment with the FIREX-I system and the LFEX laser system that utilizes Chirped Pulse Amplification (CPA) technique. In parallel, JAEC is promoting the development of human resources and industry competitiveness for future, through cooperative activities for training and education in fusion science and technology among fusion laboratories and research universities, as well as collaborative activities among universities, fusion laboratories and industries.

The Great East-Japan earthquake and the resulting tsunamis on March 11, 2011 caused an unprecedented severe accident at the Fukushima Daiichi nuclear power plant of Tokyo Electric Power Company. The accident caused radioactive contamination of a wide area of the land around the plant, and about 150,000 people are still out of home. It was recognized that though the accident was triggered by a massive force of nature, it was existing weaknesses regarding defense against natural hazards, accident management and emergency response that allowed the accident to unfold as it did. Operators of existing plants evaluated the design and safety aspects of plant robustness to protect against and mitigate the effects of severe natural events and are introducing additional measures to strengthen plant safety and enhance emergency preparedness.

The continuous reports on the status of sufferers and the critical review of the cause of the accident resulted a great shift of the public opinion such that the Japanese public no longer imagines nuclear to be a long-term option. JAEC believes it is a responsibility of Japan to contribute to the strengthening of nuclear safety worldwide by sharing its experience and lessons derived from the accident with the world and to the innovation of nuclear energy technology through R&D activities including those for fusion energy for the benefit of the global community.

K.Mo_A2

The National Ignition Facility: Transition to a User Facility and the Future of HED Laser Systems*

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The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) has been operational since March 2009 and has transitioned to a user facility supporting ignition, high energy density (HED), national security, and fundamental science and applications. The facility has exceeded its design goal of 1.8 MJ and 500 TW of 3ω light on target, and has performed target experiments with 1.9 MJ at peak powers of 410 TW. The facility is on track to perform over 300 target shots each year in support of all of its user communities. The facility has over 65 diagnostic systems operational and has shown flexibility in laser pulse shape and performance to meet the requirements of its multiple users. Progress continues on its goal of demonstrating thermonuclear burn in the laboratory. It has performed over 40 indirect-drive experiments with cryogenic-layered capsules. Over 60 new experimental platforms are being developed for HEDS and fundamental science. Equation of state and material strength experiments have been done on a number of materials with pressures of over 50 MBars obtained in diamond, conditions never previously encountered in the laboratory and similar to those found in planetary interiors. Experiments are also in progress investigating radiation transport, hydrodynamic instabilities, and direct drive implosions. NIF continues to develop as an experimental facility. An 8-beam high energy (~10kJ, high peak power (multi-petawatt) Advanced Radiographic Capability (ARC) is now being installed on NIF for producing high-energy radiographs of the imploded cores of ignition targets and for short pulse laser-plasma interaction experiments. Other new diagnostics such as x-ray Thomson scattering, low energy neutron spectrometer, and multi-layer reflecting x-ray optics are also planned. Very importantly, improvements in laser performance such as improved optics damage performance and back reflection control are being pursued that could result in NIF increasing its energy to over 3 MJ and 750 TW in the nanosecond regime. In addition, studies are on going to study NIF laser beams in creation of 100 PW-class laser light sources using the NIF as a driver for high energy laser particle accelerators and other applications. Finally, concepts in high repetition rate, high average power systems will be discussed that will be fundamental to the development of the HEDS and fusion energy fields.

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HiPER: progress towards IFE in Europe

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HiPER is the European ESFRI project that aims to demonstrate the commercial potential of power production from laser driven "inertial" fusion.

The project has now concluded its Preparatory Phase and a programme of Technology Development is commencing that aims to reduce the technological risks to the level required to attract funding for construction.

This paper will summarise the key technological and scientific progress achieved during the Preparatory Phase, describe the plans for the next phase of the project and identify the key milestones on the path to construction.

The Ignition Physics Campaign on NIF: Status and Progress*

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A primary goal of the Inertial Confinement Fusion (ICF) program on the National Ignition Facility (NIF) is to implode a low-Z capsule filled with ~ 0.2 mg of DT via laser indirect-drive ICF and demonstrate fusion ignition and propagating thermonuclear burn with a net energy gain (fusion yield/input laser energy > 1). This requires assembling the DT fuel into a dense shell of ~1000 g/cm^3 with an areal density (ρR) of ~1.5 g/cm^2, surrounding a lower density hot spot with a temperature of ~10 keV and a ρR ~0.3 g/cm^2, or ~ an a-particle range. Achieving these conditions demands precise control of laser and target parameters to allow a low adiabat, high convergence implosion with low ablator fuel mix.

At the end of the National Ignition Campaign on September 2012, we had demonstrated implosion and compressed fuel conditions at ~ 80-90% for most point design values independently, but not at the same time. For low mix implosions the nuclear yield was a factor of ~3–10X below the simulated values and a similar factor below the alpha dominated regime. The principal reason for this appears to be a hot spot density, and therefore pressure, that is a factor of ~2-3 below the simulated values, although the stagnation pressure scales with implosion velocity as expected. Ablator mix into the hot spot was also observed at lower velocities than predicted, and correlated strongly with the measured ion temperature and yield. This trend can be reproduced in simulations in which the hot spot mix has been artificially enhanced. Indications are that this mix was being driven by hydrodynamic instability at the ablation front. Angular measurements of down-scattered neutrons indicate that there could be low spatial mode asymmetries in the compressed main fuel, which may explain some of the deficit in pressure and the larger than expected mix.

Since that time, the theoretical and experimental effort has been focused on understanding the underlying physics issues responsible for the deviation from modeled performance. We will provide an overview of the current progress of the X-ray drive ICF program, and in particular discuss the results of studies to understand and control the low mode shape of the implosion due to time-dependent X-ray drive symmetry, and the subsequent impact on low-mode fuel shape, and mix. We will also discuss how these results are influencing the direction of the experimental program.

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O.Mo_A5

Indirect drive exploding pusher on the NIF

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The indirect Drive Exploding Pusher (IDEP) is a new experimental platform fielded on the National Ignition Facility to study capsule hydrodynamic performance. A vacuum hohlraum and one color laser power are used to minimize the laser-plasma interaction uncertainty due to cross beam energy transfer, while symmetry of the implosion is achieved through direct power balance between the inner and outer cones. A single shock is launched into a 120 µm thick CH capsule filled with DD or DT gas. The capsule thickness and hohlraum drive are designed so that the ablator explodes in flight and has a low convergence factor (~ 5). The neutron yield is then dominated by the shock flash/free fall yield before ablator material can mix into the fuel. On the first experiment using a DD fill, the measured laser to hohlraum coupling was 99%, and the measured neutron yield came within 15% of the yield predicted by simulations using an undegraded drive. Results and hydrodynamic simulations of this new experimental platform will be presented. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.

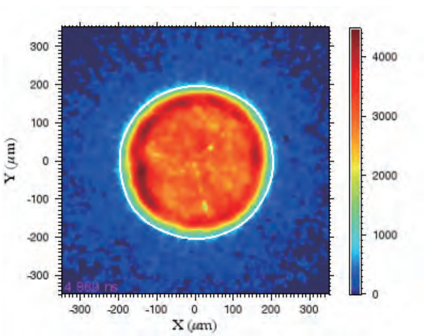

Figure 1: Polar view of the compressed capsule at bang time (4.7 ns).

O.Mo_A6

Rugby hohlraum campaign on the National Ignition Facility: status and comparison with modeling*

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A campaign is underway on the National Ignition Facility (NIF) to assess the performance of rugby-shaped hohlraums compared with conventional cylinder hohlraums. A rugby hohlraum has nearly 30% less surface wall area than a similar-diameter cylinder hohlraum, which translates into ~20% more coupling efficiency [1]. Experiments performed on the Omega laser facility comparing rugby and cylindrical gas-filled hohlraums driven by high-contrast laser pulse shaping have confirmed, if not exceeded, this expected improvement [2]. Currently, experiments on the NIF point to a nearly 17% unexplained deficit in hohlraum-to-capsule coupling that leads to slightly lower peak fuel implosion speeds than required for achieving ignition [3]. Therefore, an interest in rugby hohlraums as a platform for overcoming this deficit and increasing ignition performance margins has arisen. The initial rugby experiments are using an oversized “700” (or 7.0 mm diameter) hohlraum compared with standard “575” cylinders to maximize the case-to-capsule ratio for optimal x-ray drive symmetry, minimize the risk of significant plasma-mediated laser backscatter, and to ensure robust inner cone propagation to the hohlraum waist without requiring significant levels of crossed-beam energy transfer between the overlapping low- and high-incidence angle laser cones near the (two) laser entrance holes [4]. Provided the rugby hohlraum performance meets several key metrics in implosion symmetry and backscatter control, the next phase in the campaign is to reduce the diameter of the rugby hohlraum for improving the coupling efficiency. Progress on modeling the experimental campaign to date is described.

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

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O.Mo_A7

Backlit pinhole imaging of imploding NIF capsules

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A new platform to obtain backlit pinhole images of imploding capsules has been designed and implemented at the National Ignition Facility. The capsules consist of spherical plastic shells, approximately 2 mm in diameter, which contain either a THD ice layer or a D_2 and ^{3}He gaseous fill. The capsules are imploded by radiation or "hohlraum" drive using a shaped ignition pulse with up to 1.6 MJ in 184 of NIF's 192 laser beams. The remaining beams are redirected to a thin germanium foil 6-12 mm from capsule center in the equatorial plane, creating an area backlighter of 10.3 keV Ge He-α x-rays approximately 1 mm in diameter. A pinhole array projects the backlit imploding capsule onto a gated x-ray detector to capture radiographic images at shell radii between 300 and 100 μm with 25 μm, 100 ps resolution.

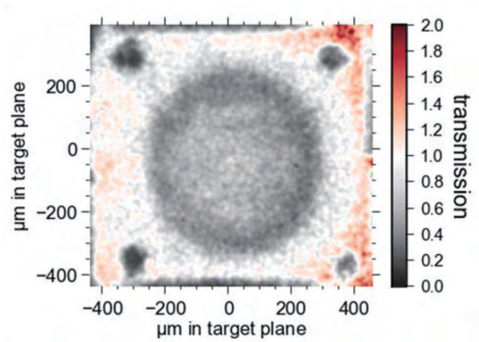

Figure 1: X-ray backlit image of an imploding NIF capsule shell, approximately 0.6 ns before stagnation. The shadows in the corners are from reference fiducials on the viewing windows.

The sequence of time-gated backlit pinhole images is analyzed for implosion velocity, low-mode shape and areal density asymmetries, and any absolute offset and drift velocity of the imploding capsule. The resulting data complement capsule self-emission images and backlit slit images. It is common for the backlit shell radiograph and the self-emission shape – viewing from the same direction – to have significantly different Legendre mode structure. The platform has been used to measure the sensitivity of low-mode shape to various drive parameters such as hohlraum geometry and beam pointing. For example, we have performed a hohlraum length scan from −0.3 to +1.0 mm around the nominal 9.43 mm length that shows the in-flight Legendre P4 amplitude of the imploding capsule at a radius of 200 μm reduced from 17 to 2 μm.

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O.Mo_A8

Probing matter at Gbar pressures at the NIF

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Laboratory measurements of the Equation of State (EOS) of matter at high pressure, exceeding several hundred Mbar, is of great importance in the understanding and accurate modeling of matter at extreme conditions. Of central importance is benchmarking dense matter models in the regime that is relevant for fusion energy experiments, which assemble material to the highest densities and pressures ever achieved in the laboratory (hundreds of g/cc and >100 Gbar).

In this work we present a platform to measure the material properties, specifically the equation of state and electron temperature, at extreme pressures of ~Gbar at the National Ignition Facility (NIF). In these experiments we launch spherically convergent shocks into solid CH or diamond samples, using a hohlraum radiation drive, in an indirect drive laser geometry. X-ray radiography has been applied to measure the shock speed and infer the mass density profile, enabling determining of the material pressure and Hugoniot equation of state. X-ray scattering will be applied to measure the electron temperature through measurement of the electron velocity distribution. The first experimental measurements at pressures of several hundred Mbar will be presented.

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CAPSULE ABLATOR PERFORMANCE VIA STREAKED RADIOGRAPHY EXPERIMENTS OF INDIRECT DRIVE ICF IMPLOSIONS ON THE NATIONAL IGNITION FACILITY *

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Streaked 1-dimensional (slit imaging) time resolved radiography of 1.1 mm radius capsule in ignition hohlraums [1] that was recently introduced on the National Ignition Facility (NIF) gives an inflight continuous record of implosion velocities, ablator shell thickness and remaining ablator mass in the last 3-5 ns before peak implosion time [2]. As shown in Figure 1, streaked radiography can be timed to capture also the self-emission at the peak implosion time and during the explosion phase, giving insight into the hot spot dynamics.

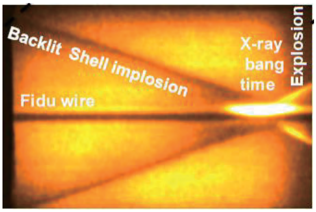

Figure 1: 1D Backlit streaked radiograph of capsule implosion on the NIF (1.2 mm vertical field-of view, 2.8 ns horizontal time window).

Specifically, the in-flight performance of Si doped CH capsules will be compared for various Si dopant concentrations, drive pulse lengths and for low and high adiabat implosion designs, at peak implosion velocities relevant for ignition point designs [2]. Furthermore, in-flight CH capsule performance will be compared to alternate ablator data such as high density diamond (HDC) in the context of the "rocket efficiency" [3], peak velocity vs ablator mass at velocities relevant for ignition point designs [2].

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IONISATION DEPRESSION, OPACITY, AND COLLISIONALITY IN AN X-RAY GENERATED SOLID-DENSITY PLASMA

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We have used the Linac Coherent Light Source (LCLS) X-ray Laser to generate solid-density aluminum plasmas at electron temperatures between 100 and 200 eV. [1] Observation of the K-shell fluorescence as a function of LCLS photon energy (both above and below the K-edge of cold Al at 1560-eV) provides a plethora of rich physics, revealing detail of the ionization states, and affording a direct measurement of the ionization potential, and hence the ionization potential depression of each charge state. [2] The IPDs found via this technique are far greater than those predicted by the widely used Stewart-Pyatt Model. Furthermore, the LCLS intensity is so great that copious K-shell fluorescence can be generated by resonantly pumping the K-α transitions, even when those transition energies lie below the cold K-edge. [3] The sensitivity of the K-α yield of each successive charge state to the LCLS photon energy is sufficient to enable us to view the effect of the increasing collisionality of the plasma, such that we can observe the generation of a K-shell core hole by an LCLS photon, followed by collisional ionization of the L-shell, before the K-shell hole is filled via K-α emission. We discuss the prospects of using these techniques to further our understanding of plasmas at a few hundred eV, and solid density - the very density and temperature conditions that exist half-way to the centre of the sun.

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O.Mo_B3

First-principles compression measurements of shocked Aluminum using spectrally and angularly resolved x-ray Thomson scattering

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Direct measurements of the relative strength in the ionic structure factor at various scattering angles is important for accurate calculations of material properties in the high pressure and temperature phase. We will demonstrate the ability to measure the ion-ion correlation peak using simultaneous angularly, temporally, and spectrally resolved x-ray scattering measurements in laser-driven shock-compressed aluminum.

Molybdenum He-alpha (17.9 keV) x-rays have been used to probe Al foils that are compressed using both single and double (counter propagating) shocks in a forward, small angle, scattering platform with very high angular precision. In our study, 125 μm thick and 200 μm thick Al targets were compressed 3.5x and 7x the solid density using 1 ns pulses with a total laser energy of 4.5 kJ and 9 kJ respectively. A total drive intensity of 3×10^{14} W/cm^2 on each irradiated aluminum surface was used to drive shocks into the sample while 7×10^{14} W/cm^2, incident on a thin Mo foil, was used to generate Mo He-a x-rays at 17.9 keV, in order to probe the compressed targets. We observe a well-pronounced peak in the static structure factor at a wave number of k = 4 Å^{-1}. The magnitude of this correlation peak is in good agreement with calculations that use a potential with strong short range repulsion.

The results will show that the elastic x-ray scattering amplitude, angularly resolved, shifts to higher wave number with increasing density, while the width and peak amplitude can provide information on the temperature and ionization state. By doubling the density of the Al (using counter propagating shocks), the ion-ion correlation peak can demonstrate an observable shift corresponding to the geometry used in this experiment. This presents a new scattering diagnostic to fully characterize states of matter at densities and temperatures that have not been previously accessible.

O.Mo_B4

Fast computation of radiative properties and EOS of warm dense matter using the ATMED code

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The ATMED code has been developed to compute the spectral radiative opacity as well as the Rosseland and Planck means for single- and multi-component hot dense plasmas. The code has been developed in the context of the Average Atom Model. The required atomic data are computed using a Relativistic Screened Hydrogenic Model based on a new set of universal screening constants including j-splitting that were obtained from the fit to a wide database of atomic energies, ionization potentials and transition energies of high quality [1]. The total spectral opacity of plasma $\kappa(\nu)$ is computed as the combination of bound-bound, bound-free, free-free and scattering processes. The line absorption cross section is computed using a new analytical expression for oscillator strengths based on relativistic screened-hydrogenic wave functions [2]. The lineshape includes natural width, Doppler line broadening and electron collisional broadening. To obtain a more realistic value of the Rosseland mean opacity and additional broadening of the bound-bound transitions has been included by considering the fluctuations of the occupations numbers into the atomic shells [3]. The model can also compute the Plasma Equation of State and Shock Hugoniot curves. It uses the Cowan ion equation of state to compute the ion contribution and the electron ionization-equilibrium EOS is taken from the Thomas–Fermi model with a semiempirical bonding correction in a form proposed by Barnes [4]

The model has been successfully tested and an applied to study several problems which arises in ICF reactor design such as the radiative behaviour of the target-chamber gas-fill used to moderate the first-wall heat-pulse due to x-rays and energetic ions released during target detonation, or the properties of plasma mixtures of elements which are of interest for radiation driven imploding shells (ablators) of ICF capsules, indirect drive hohlraum cavities or X-pinch plasma produced by exploding wires. In spite of its simplicity, the model provides the correct order of magnitude of relevant quantities, so it can be used to model radiative transport phenomenon in hydrodynamic codes and experiments in an approximate way. In this paper we show the main features of this code as ICF design tool.

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Orion: a high contrast user facility

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The Orion facility consists of two synchronized laser systems, a 2 beam sub-ps system with a 10 beam ns pulse system . Two CPA (Chirped Pulse Amplification) beamlines each deliver 500J to target in a 0.5ps pulse (1PW) at 1053nm. The beams are focused to a ~10μm spot achieving a target intensity of >10^{21} Wcm^{-2}. Ten long pulse beamlines each deliver 500J in 0.1-5ns temporally shaped pulse at 351nm. The long pulse beamlines can be operated in several configurations. The baseline configuration has all ten long pulse beams delivering the same temporal shape with a controllable inter-beam delay of up to 10ns. Alternatively two bundles of 5 beamlines are each driven by a separate front end generating a different pulse shape with an arbitrary delay between the two bundles. A third configuration seeds the short pulse beamlines with long pulses enabling them to be run as two additional long pulse beamlines.

Orion was designed with the option to enhance the contrast of one of the CPA beamlines by frequency doubling post compression. The compressed pulses are apodized to 300mm diameter then frequency doubled using a 320mm diameter, 3mm thick KDP crystal. The frequency conversion process has an efficiency of ~70%, generating ~100 J, 0.5 ps, 527 nm laser pulses with a nanosecond contrast of 10^{14}.

Further development work is in place to install an OPA with a pump pulse of a few picoseconds at the front end of the short pulse beamlines to enhance the contrast by ~10^4 in the fundamental wavelength. This is expected to be in place by the end of the year and, if used in conjunction with frequency doubling will push the contrast beyond our measurement capability.

The facility was commissioned in 2012 with all beamlines operating at nominal performance. A capability experiment has been carried out to demonstrate operational efficiency and the conditions achievable with the laser. Orion is now open as a user facility capable of firing up to five multi-beamline shots per day. From March 2013 15% of the facility operating time will be given over to external academic users in addition to collaborative experiments with AWE scientists.

Progress on the Apollon-10PW laser facility

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The Apollon-10P is a laser infrastructure aiming to realize experiments at 10 PW peak power. It will produce ultra intense and ultra short sources of particles (electrons, protons...), coherent and high energetic X rays. This laser facility is a multi beam line composed of one main laser expected to deliver on target 10PW pulses at 1 shot per minute repetition rate (150J in 15fs at 800nm), a 1 PW beam line, a probe with 10TW and an uncompressed beam (energy up to 250J, ns). A collaborative consortium consisting of three Laboratories mentioned in the author's affiliations does the development and the construction of this laser system.

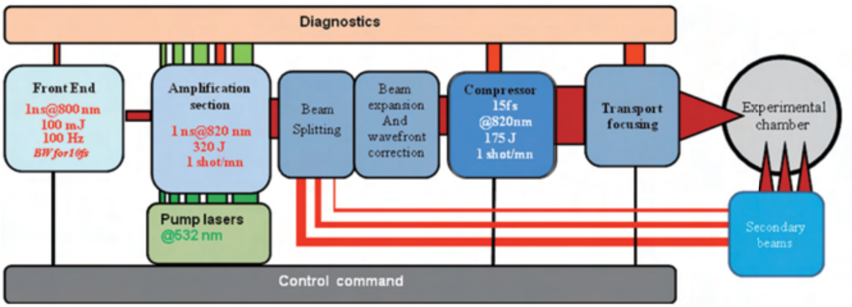

Figure 1: General scheme of the Apollon-10P laser system

The laser is based on a hybrid OPCPA- Ti:Sa architecture in order to produce 150 joules in 15fs at 1 shot every minute.

The front-end will generate 10 Hz repetition rate pulses with 100-mJ energy and a spectrum suitable with 10fs pulse duration. This will be obtained via OPCPA in BBO crystals that are pumped by diode-pumped solid-state lasers. These pulses will then be amplified in 5 Titanium doped sapphire multipass systems to 300 joules while preserving the spectral properties. The compression will then be obtained by a large unfolded and under vacuum compressor.

The status of the construction will be described by relating the latest results and discussing the advances on the key points of the laser system, as the DPSSL for OPCPA, ASE in large TiSa crystals, control of the spectrum, high energy pump lasers, stretching and compression issues, adaptive optics for large beams. The implementation of the laser system in the dedicated building at l'Orme des Merisiers and the related experimental areas will be presented.

O.Mo_C3

Development of 4 PW CPA Ti:sapphire laser system

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The development of PULSER (PW Ultrashort Light Source for Extreme Science and Research) which was a chirped pulse amplification (CPA) Ti:sapphire laser system was complete in 2012. PULSER is composed of two PW beamlines which are named PULSER I and PULSER II. PULSER I produced the 1 PW peak-power at 0.1 Hz with 96 J pump energy [1]. The output power of PULSER II reached the 1.5 PW with 120 J pump energy [2]. Now, PULSER II is being upgraded for a wider range of science in the laser-matter interaction through the project of Institute for Basic Science (IBS). After PULSER II is upgraded, the output power is expected to be 4 PW. For this goal, the output energy is increased by adding a booster amplifier and the laser spectrum is broadened by using the optical parametric chirped pulse amplification (OPCPA) technique and the cross polarized wave (XPW) generation. For suppressing the parasitic lasing which is the main bottleneck in a large aperture Ti:sapphire amplifier, the refractive index matching liquid and the absorption dye is used as the crystal cladding and the pump energy fluence on a Ti:sapphire crystal is decreased. In this conference, we will present the status of PULSER and the development of 4 PW CPA Ti:sapphire laser system.

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O.Mo_C4

ELI-Beamlines: Extreme Light Infrastructure Science and Technology with ultra-intense Lasers

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We will be giving an overview on the development of the "ELI-beamlines facility" [1] built within the Extreme Light Infrastructure (ELI) project based on the European ESFRI (European Strategy Forum on Research Infrastructures) process.

ELI-Beamlines will be a high-energy, repetition-rate laser pillar of the ELI (Extreme Light Infrastructure) project [2]. It will be an international facility for both academic and applied research, slated to provide user capability since the beginning of 2018. The main objective of the ELI-Beamlines Project is delivery of ultra-short high-energy pulses for the generation and applications of high-brightness X-ray sources and accelerated particles. The laser system will be delivering pulses with length ranging between 10 and 150 fs and will provide high-energy Petawatt and 10-PW peak powers. For high-field physics experiments it will be able to provide focused intensities attaining above 10^{22} Wcm^2, while this value can be increased in a later phase without the need to upgrade the building infrastructure to go to the ultra-relativistic interaction regime in which protons are accelerated to energies comparable to their rest mass energy on the length of one wavelength of the driving laser. The design concepts and designs for different areas including building, lasers, beam distribution and secondary source beamlines for this new user's facility will be discussed. We will focus on experimental opportunities in plasma and high density physics that will be possible when combining both 10-Hz PW beamlines and the kilojoule beamline. The status and timelines of the project delivery will be presented.

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P.Mo_1

The simulations of indirect-drive targets for ignition on megajoule lasers

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The thermonuclear ignition of indirect-drive targets has not been achieved during three-year researches carried out under NIC program in USA. The experiments performed on NIF laser with cryogenic targets placed in cylindrical hohlraum indicate the necessity of the improvement of compression symmetry and/or the increase of margins for thermonuclear ignition.

The results of numerical simulations of indirect-drive targets for thermonuclear ignition on megajoule lasers are presented. The calculations were performed with use of 1D- and 2D- radiation hydrodynamic codes developed in RFNC-VNIITF [1]. The analysis of published calculations of indirect-drive targets, which were offered to obtain a thermonuclear energy yield above 20 MJ on NIF and LMJ lasers, has shown that these targets have very low margins for thermonuclear ignition. For example, these targets could not be ignited under decreasing of thermonuclear reaction rate less than in 2 times according to even 1D-calculations executed with use of ERA code [2]. The requirements to accuracy of a target manufacturing and a symmetry of it irradiation were studied by means of the 2D-TIGR-OMEGA-3T codes [3]. The calculations of compression and thermonuclear burning of targets are carried out with using of these codes for conditions of the X-ray flux asymmetry obtained in the simulations of the Rugby hohlraum that were performed with 2D- SINARA code [4].

The purpose of new calculations is search of indirect-drive targets which have the raised margins for ignition at the expense of decrease of requirements to a thermonuclear energy yield. The necessity of these researches is caused by the construction of the magajoule laser in Russia for a thermonuclear ignition of direct- and indirect-drive targets [5].

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P.Mo_3

Design and Analysis of a Novel Directly Driven Target with Enhanced Radiation

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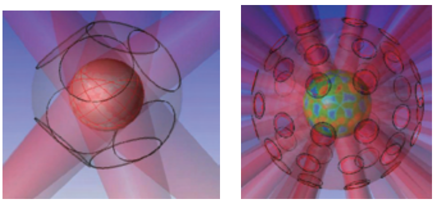
In the process of laser directly driven fusion, comparable amounts of energy will loss due to laser scattering, which may even approach about 30 percent of its total energy [1]. In addition, the driven symmetry on the capsule is also very low because of the non-uniformity of laser radiation, which may worsen the symmetry of the capsule implosion [2].

A novel directly driven target with enhanced radiation is designed in this paper. Based on the design of direct drive targets, a spherical gold hohlraum with enough laser entrance holes is built to enable the laser injection without any intersection, and enclose the capsule in the great extent. Such spherical hohlraum addition can be utilized to absorb the partial energy of scattering lasers, and generate X-ray to re-radiate the centrally located capsule, in which the efficiency of lasers and the drive symmetry of the capsule can be significantly improved.

Finally, two new targets on the ShenGuangIII prototype (SG-III YX) laser facility and the national ignition facility (NIF) laser facility seen in Figure 1 are designed and analyzed on the incident flux and driven symmetry of the capsule. And the resulting incident flux and drive symmetry can be improved from 10 percent to 30 percent.



(a) for the SG-III YX (b) for the NIF

Figure 1: The scheme of directly driven target with enhanced radiation.

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High-Density Carbon (HDC) Ablator for NIC Ignition Capsules

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HDC ablators show high performance based on simulations. Simulations must include higher M-band radiation compared to that for plastic capsules, because of the shorter pulses for HDC capsules. HDC capsules have good 1-D performance because HDC has relatively high density (3.5 g/cc), which results in a thinner ablator that absorbs more radiation. High HDC density provides high hydrodynamic impedance mismatch between the ablator and the fuel. This reduces the 1^{st} shock strength in the fuel and consequently fuel entropy can be minimized. HDC ablators have good 2-D performance because the ablator surface is more than an order-of-magnitude smoother than Be or plastic ablators. To prevent unacceptable pre-heat from M-band radiation, it is necessary to dope HDC ablator with W or Si. Capsules have been fabricated demonstrating that a spherical HDC shell can be uniformly doped with the required concentration of 0.3 at% of W. In simulations, this type of capsule can tolerate more than 200 ng of W-doped ablator material mixed into the hot spot and still gives full YoC, based on detailed nlte modeling of W radiation. For our ignition design with W dopant: peak velocity = 0.39 mm/ns, mass weighted fuel entropy = 0.46 kJ/mg/eV, peak core hydrodynamic stagnation pressure = 780 Gbar, and yield = 19 MJ. The remaining ablator fraction is about 7% at peak velocity. Refreeze of the ablator near the fuel region can be avoided by appropriate dopant placement since dopant can lower the HDC melt temperature. 2-D simulations show that yield is close to 90% 1-D YoC even with 3x nominal surface roughness on all surfaces. A preliminary HDC experiment was conducted in early March and showed low level of SBS, and nominal SRS. First HDC ConA (convergent ablator) and keyhole experiments will be conducted in Spring 2013.

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P.Mo_5

Ignition Calculations using a Reduced Coupled-Mode Electron-Ion Energy Exchange Model

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In ICF implosions, high convergence compression of the capsule fuel accesses both high density and degenerate states. Under these conditions the standard Spitzer-like plasma physics models of energy transport and exchange processes are unlikely to be valid and coupled-mode models based on quantum kinetic treatments can differ significantly from Spitzer [1]. However, it is difficult to assess the impact of such models on performance since full numerical evaluation is computationally expensive and unsuitable for direct implementation in radiation-hydrocodes.

We consider a recently developed reduced coupled-mode model for electron-ion energy exchange [2] which accurately reproduces full numerical results over a wide range of density and temperature space, including a coupled-mode effect not seen with other reduced models. The reduced model has been implemented in the Nym hydrocode and used to assess the impact on ICF fuel assembly and performance.

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P.Mo_6

Plasma physics effects on fusion yield rate

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Fusion yield in inertial confinement fusion primarily comes from the reaction between deuterium (D) and tritium (T). The yield rate is $p_f = n_D n_T \langle \sigma v \rangle E_f$ with $n_{D,T}$ the number densities of D and T, $\langle \sigma v \rangle = \int \int \sigma |\mathbf{v}_D - \mathbf{v}_T| f_D f_T d\mathbf{v}_D d\mathbf{v}_T$ the fusion reactivity integral, and E_f the energy release per fusion reaction. The DT fusion yield rate is affected by plasma physics through the product of n_D and n_T, and the normalized ion velocity distribution $f_{D,T}$ in the fusion reactivity integral. This is in addition to the well-known fusion criteria of multi-keV ion temperature at which the σ becomes large enough to initiate burn. In conventional radiation-hydrodynamic modeling of thermonuclear burn, the ratio of n_D and n_T is fixed by initial condition, and $f_{D,T}$ are assumed to be local Maxwellians, so only the overall ion temperature and density enter the fusion yield rate.

Here we give a summary of our recent work addressing these three plasma physics effects on yield rate. (1) Fuel ion (D & T) separation: Although ICF target initially has the optimal $n_D = n_T$, target assembly by implosion introduces powerful thermodynamic forces that drive inter-species ion diffusion. These are baro-diffusion driven by ion pressure gradient, electro-diffusion driven by induced plasma ambipolar electric field, and thermo-diffusion driven by both ion and electron temperature gradients. We have recently derived the fundamental transport equation for inter-species diffusion, along with the baro-, electro-, and thermo-diffusion coefficients [Kagan & Tang, PoP **19**, 082709 (2012); PRL **109**, 269501 (2012)]. (2) Tail ion depletion: The rapid increase in DT cross section with relative ion energy dictates that high-energy tail ions dominate fusion reactivity. Retaining the fusion-producing high energy tail ions in a hot spot is, however, a substantial challenge since their mean-free-path is considerably longer. The free streaming loss of tail ions from the hot spot into the surrounding cold fuel/pusher, also known as the Knudsen layer effect, can significantly deplete the hot-spot tail-ion population, producing order-unity fusion reactivity degradation. We have developed a hierarchy of Fokker-Planck models and solved them in typical ICF hot spot/fuel layer configuration [Tang et al. preprint & McDevitt et al. preprint]. A number of subtle effects by ambipolar electric field, pitch angle scattering, and nonlocal yield recovery have been identified and quantified. (3) Mitigating hot spot thermal loss and hydrodynamic mix: A primary obstacle in ICF ignition is the deleterious role of hydrodynamic mix in limiting the hot spot temperature. Our recent calculations have shown that Rayleigh-Taylor (RT) instability at the hot spot/fuel layer interface can self-generate a magnetic field aligned with the interface via the Biermann battery [Srinivasan, Dimonte, Tang, PRL **108**, 165002 (2012)]. The field strength is sufficient to magnetize electrons and reduce the electron thermal conductivity by a factor of 1-10 [Srinivasan & Tang, PoP **19**, 082703 (2012)]. This helps mitigate the cooling effect of RT mix. With a stronger external field of about 10 tesla, implosion of convergence ratio 10 can compress the field to 1000 tesla. We find [Srinivasan & Tang, PoP, in press] that the RT instabilities at the hot spot/fuel layer interface can further amplify the field to 20000 tesla and align it to the mix interface. This field has the additional benefit of stabilizing short wavelength RT modes, and drastically reduces RT mix. This research was supported by LANL LDRD and DOE NNSA.

P.Mo_7

Hybrid MHD and Kinetic Modeling in ICF

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We present a suite of computational tools used for the modeling of neutron spectroscopy and alpha particle transport in inertial confinement fusion implosions. Kinetic models of these effects are coupled to the MHD code Gorgon to provide 3D simulations of the implosion and burn phases.

Neutron emission spectra are calculated from the Gorgon simulations using a relativistic model for the neutrons produced by a thermal plasma. This model includes the effects of thermal broadening and fluid motion on the neutron spectrum. Accurate modeling of the neutron spectrum allows additional diagnostic information to be obtained when interpreting the neutron spectrum. It is shown that the shape of the high energy tail of the neutron spectrum (> 14.5 MeV) can be an accurate measure of the temperature of the burning plasma. Similarly, the ratio of FWHM of the DT and DD neutron spectra can be used to identify sources of spectra broadening other than thermal. These sources include broadening due to fluid motion. In addition, the model is used to identify the sources of nonthermal neutron production in Z-pinch plasmas.

Alpha particle heating and transport is modeled by coupling a PIC model to the Gorgon code in which the alpha species is treated as PIC particles. This model fully resolves the dependence of the energy deposition rate on the alpha particle energy and allows for an anisotropic distribution of alpha particles within a computational cell. In addition, the effects of finite mean free paths and the motion of alpha particles due to electromagnetic fields are included. Such fields are generated by the large temperature and pressure gradients found near instabilities on the hotspot edge.

P.Mo_8

Relativistic corrections to Coulomb collision rates in inertial confinement fusion

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At the temperatures required in inertial confinement fusion (ICF) in order to achieve burn, the electrons become weakly relativistic. In this work we outline the effect this has on the various underlying microphysics, focusing predominantly on Coulomb interactions. We discuss the processes of charged particle stopping, thermal equilibration and transport. Corrections to their classical rates are presented, which may straightforwardly be used in existing codes. In the regime of interest these remain modest for stopping and equilibration, but can be much more significant for transport coefficients (including thermal conductivity). By use of numerical simulations, we analyze the expected implications of these corrections for burn in ICF.

P.Mo_9

Tuning the early-time radiation drive of an ignition hohlraum on the National Ignition Facility*

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Early time drive asymmetries in the radiation drive can introduce swings in the low-mode shape of an ignition capsule during the peak of the drive. These may cause large areal-density variations of the dense fuel thereby quenching ignition. As a result, an extensive effort has been underway at the National Ignition Facility (NIF) to tune the first 2 ns of the laser drive. By replacing the ignition capsule with a high-Z sphere [1] we have performed so-called re-emit experiments that directly measure the early-time equatorial and azimuthal asymmetry of the radiation drive in an ignition hohlraum. The NIF was designed with a large number of beams grouped into two sets of two cones (inner and outer) entering the hohlraum from two opposite laser entrance holes (LEH). The illumination pattern thus obtained consists of three rings, one at the equator (created by the two inner cones, mainly responsible for the azimuthal symmetry) while the other two rings (consisting of outer cones) are appropriately located at either side of the equator to cancel out some low-mode asymmetries (typically Legendre mode 4 (P4) at the time of maximum laser drive). The power ratio between the equatorial and side rings can then be adjusted to control the lowest order equatorial mode (P2) at various times during the laser pulse. To control the cone fraction in the peak we set the wavelength of the cones to transfer laser energy typically from the outer to the inner cones [2]. Recently we reported on re-emit experiments to assess and tune P2 in a variety of hohlraum configurations [3]. It was found that with the wavelength separation set to minimize the P2 in the peak of the laser pulse there is significant energy transfer during the picket of the laser pulse, which decreases the input inner cone fraction to 10%. The azimuthal asymmetry in NIF hohlraums is very small since each cone of laser beams is arranged to completely cover the hohlraum wall azimuthally. Nonetheless, experiments of ignition-like capsules have shown imploded core shapes with significant amounts of the azimuthal mode 4, which has been minimized by changing the wavelength separation within the two inner cones. To assess how this wavelength configuration influences the early time azimuthal symmetry several re-emit experiments have been performed. Additionally, for layered targets, a “starburst” pattern is required to diagnose the quality of the fuel ice layer. This feature, consisting of a number of open slots located at four azimuthal angles around the hohlraum, can also lead to an early-time radiation asymmetry. In this paper we will present results from our foot symmetry experimental campaign and compare them to our 3D simulations.

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P.Mo_10

Effects of mode 1 drive asymmetry on NIF implosions

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Radiation drives showing a top-to-bottom, or mode 1, asymmetry are deleterious to implosions on the National Ignition Facility. Numerical simulations using HYDRA show that mode 1 x-ray drive perturbations push the central hot spot away from the direction of highest x-ray drive. These disturbances produce areal density variation in the cold shell and cause low-density jets to propagate through the hot spot. The altered hydrodynamics lead to implosion performance that is greatly reduced. The total neutron yield and hot spot pressure are substantially lowered. The apparent ion temperature, however, is increased by jet-induced velocity gradients in the neutron-emitting hot spot. Consequently, mode 1 perturbations can both decrease yield and increase apparent temperature simultaneously. This can help to reconcile simulated observables with those obtained from experiments.

Data captured by a number of diagnostics, including gated x-ray cameras, backscatter diagnostics, and neutron spectrometers, suggests that mode 1 asymmetries may be present in NIF implosions. While the level of asymmetry is not yet conclusive, diagnostic modifications and improvements have been made in part to test the mode 1 hypothesis. Post-processing of simulations shows that mode 1 perturbations at levels of concern in NIF will produce x-ray and neutron diagnostic signatures that are measureable by the improved diagnostics. These signatures include neutron-inferred hot spot velocity, angular variation of ion temperature, and gross in-flight translation of the imploding shell.

The improved diagnostic suites will be exercised on a number of shots designed to test the mode 1 hypothesis. The experiments will use both controlled, nearly spherical x-ray drive and intentionally asymmetric drive to measure the effects of such perturbations on the diagnostic signatures. The experiments will include two cryogenically layered DT implosions awarded by the NIF New Initiative Program to directly test the impact of mode 1 perturbations and their interactions with other low-mode asymmetry. Prepared by LLNL under Contract DE-AC52-07NA27344. LLNL-ABS-628572.

Measuring the azimuthal symmetry of the imploding in-flight ablator with a novel axial x-ray shadowgraph platform on the National Ignition Facility

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In order to achieve the high compression required for thermo-nuclear ignition in inertial confinement experiments, the control of low-mode asymmetries is crucial.

For x-ray driven implosions, the hohlraum typically has cylindrical symmetry, and the x-ray drive on the capsule is close to axisymmetric. However, realistic targets have azimuthally asymmetric structures (such as a finite number of laser beams, diagnostic holes in the hohlraum wall, and the fuel fill tube attached to the equator of the capsule), all of which can compromise the ability to compress the capsule. Therefore, to control the low-mode azimuthal asymmetry of the imploding shell, it is very important to measure these asymmetries. In addition to achieving a "round shape" at a specific time (e.g. at the maximum velocity time or the maximum compression time) we also need to measure angular distribution of the shell's mass and velocity.

To measure the time-dependent shape, velocity, and mass, we have developed a new axial x-ray shadowgraph platform at the National Ignition Facility. We set the x-ray backlighter foil on the hohlraum axis (below the laser entrance hole) and observe the backlit image using a gated x-ray camera placed above the hohlraum. The experimental design and detailed results from this new experimental platform will be presented.

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P.Mo_13

IFSA 2013 Abstract: Fast Magnetic Diffusion into ICF capsules

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Application of high B_Z fields (1 to 4 kiloTesla) at fast magnetization rates (up to several kilo-Tesla / ns) enabled by recent laser-driven coils [1] to ICF capsules can induce shallow surface diamagnetic currents which force magnetic field lines to wrap around low-field interior DT fuel, creating "magnetic bubbles", Fig.1. High induced magnetic-well mirror ratios B_{max}/B_{min} within DT fuel may be preserved under fast, flux-conserving implosions, potentially giving stagnation hot spots with thermal conduction losses (both radial and axial) suppressed, and with almost all alphas confined even with hot spot $\rho r < 0.3$ g/cm^2.

A cylindrical 1-D magnetic diffusion model with three radial zones estimates maximum magnetic well depths (mirror ratios) possible with thin diamagnetic current layers induced by very fast- rising applied fields (up to 4 kilo T/ns) into various ablators (gold, aluminum and diamond), and into solid DT cryo layers and central DT gas, for two sizes of capsules: 200 μm radius for 10-20 kJ scale laser facilities, and 900 μm radius for 1-2 MJ scale ignition facilities. Largest magnetic well mirror ratios are found in larger capsules using diamond ablators, increasing from 15 to 40 within solid DT, and from 200 to 600 within the fuel gas "bubble" with increasing applied fields up to 4 kiloTesla. Central fuel "bubbles" with such high magnetic well mirror ratios may enable enhanced alpha energy coupling and minimum thermal losses for ignition experiments with much reduced capsule hot spot convergence, ρr and pressure. Preliminary 1-D implosions with such hollow "bubble" fields will be discussed.

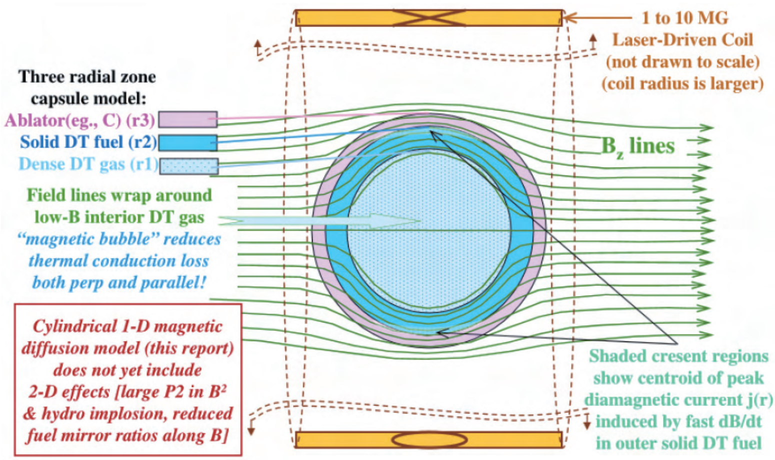

Figure 1: Sketch of ICF capsule model for fast magnetic diffusion calculations

Ref:[1] Fujioka, et.al., Scientific Reports |3 : 1170 DOI: 10.1038/srep01170, 30 Jan. 2013

P.Mo_15

Generation of high flux secondary radiation by a long laser pulse

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The PALS (Prague Asterix Laser System) iodine laser, operating at a peak power of about 2 TW (600 J, 0.3 ns, 1315 nm) and modest nominal laser irradiance ($I\lambda^2 \sim 5\times10^{16}$ W cm^{-2} μm^2) is used to generate several MeV proton/ion beams with very high current density up to few kA/cm^2 in proximity of the target. The associated gamma burst and hot electron energy reaches values of few MeV. The comparison with experimental scaling laws clearly shows that the maximum particle energy achieved in our experiment is typical of picosecond and femtosecond laser irradiances at least two orders of magnitude higher. Enhancement of the maximum particle energy can be explained by a non-linear laser-plasma interaction caused by the low laser pulse contrast ratio, resulting in a local increase of the intensity, for instance due to the self-focusing and filamentation mechanisms. The self-focusing effect is qualitatively reproduced by hydrodynamic simulations and particle-in-cell simulations. The energy spectrum and high current density of the accelerated proton beams result to be optimal for the production of extremely high flux secondary radiation. Fusion neutrons from a deuterated target and fusion alpha-particles from a hydrogen-enriched boron-doped target are observed experimentally, thus being candidates as potential high brilliance sources achievable at moderated laser intensities.

P.Mo_16

Influence of resistivity gradient on laser-driven electron transportation and ion acceleration

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Laser-driven relativistic electron transport through aluminum foils coated with CH layer and following target normal scale acceleration (TNSA) of proton in contaminants has been studied by means of two-dimensional collisional particle-in-cell (PIC) simulations. This study is motivated by recent proton acceleration experiments [S. Betti et al., Phys. Plasmas 16, 100701 (2009).] showing a significant effect of the resistivity gradient between two layers on the proton angular spread. Here, PIC simulations shows that low energy component of the fast electrons beams is clearly inhabited by the magnetic field generated due to the resistivity gradient at the interface of two layers. A sheath electrostatic field built up in the target back surface only from high energy portion of fast electrons shows fairly smooth transverse profile with respect to uncoated ones. It combined with self generated magnetic field last for a long time during and after the laser target interaction and results in the collimation of the accelerated proton beams with a much smaller angular spread.

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P.Mo_17

Transport and isochoric heating of laser-accelerated proton beams in solid targets

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Intense laser-accelerated ion beams have attracted great interest due to their many prospective applications in scientific, technological, and medical areas. Nearly all of the applications eventually require the beam to transport through and/or deposit energy in solid targets of different materials. High-intensity laser-accelerated ion beams have exceptionally high particle flux (>10^{19} particles/cm^3), which generally heat the transport cold target rapidly into a partially ionized warm dense plasma state with temperatures of ~1-100eV and ~0.1-10 times solid density. The beam transport and stopping power in this regime is highly dynamic, inherently different from what have previously been studied using low-flux beams from conventional accelerators.

In this talk, we report the theoretical and numerical studies on the transport and isochoric heating of intense laser-accelerated proton beams in solid targets. The corresponding experiment was conducted on the TRIDENT laser at Los Alamos National Laboratory. Protons from a laser-irradiated spherically curved foil were focused into a planar transport foil of varied atomic number (Z) and thickness. The XUV emission brightness from a rear Au layer coated on the transport foil decreased with Z, but so did the spot size with the Cu and Au transport foil targets producing very tightly confined emission profiles (~44 μm) compared to the Al and CH cases (~180 μm). This indicates a clear dependence of the beam transport and heating dynamics on the target material properties. To correctly model this beam-plasma interaction, a new ion stopping-power calculation module covering both the warm and hot dense plasma regimes has been implemented in the hybrid particle-in-cell code LSP [2], where both the contributions from bound and free electrons are taken into account for the total stopping power using the Bethe formula and plasma free electron term respectively. Therefore, the ion stopping power of the target varying with its temperature and ionization level can be dynamically described, i.e. with the rising ionization during the interaction, stopping power decreasing for particles at the low-energy range while increasing for high-energy range. Using this new modeling capability, the experimental observations have been well explained. The dependences of the interactions of laser-accelerated proton beam with warm dense plasmas on the beam intensities, target materials and initial target plasma temperatures have also been systematically studied.

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P.Mo_18

Three-dimensional simulations of intense laser-plasma interactions for fast ignition

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The characterization of the fast electron source is a critical aspect for fast ignition of fusion targets. A detailed understanding of the dependence of the fast electron spectrum and divergence on the laser and plasma parameters is required to optimize the source, achieve higher overall efficiencies, and design ignition scale experiments. However, this requires three-dimensional (3D) particle-in-cell (PIC) simulations of the laser-plasma interaction, which are computationally demanding; there have been few 3D studies and only for reduced scales.

We have performed a set of large 3D PIC OSIRIS simulations in order to study the fast electron source at realistic conditions. We model the interaction of an ignition scale laser with a dense plasma exceeding 100 microns in size in each direction for multiple picoseconds. We vary the laser intensity, spot size, and wavelength, as well as the plasma density in order to understand the dependence of the source properties with the laser and plasma parameters. We will discuss the detailed characterization of the source and the scaling laws obtained for the electron spectrum and divergence.

Hybrid-PIC simulations were also used to study the transport and energy deposition of a self-consistent source and determine the overall efficiency of the fast ignition process for optimized laser parameters.

These results allow for a better understanding of the source characteristics and enable the use of reduced models to optimize the fast electron transport and core heating based on a more realistic electron source.

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P.Mo_19

Systematic Study of Fast Electron Generation, Transport and Resistive Collimation Using the 10-Picosecond Kilo-Joule OMEGA EP Laser*

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Generation and transport of an intense current of fast electrons produced from a high intensity laser matter interaction are of great importance to the relativistic High Energy Density (HED) sciences, particularly for applications such as fast ignition laser fusion and creation of warm dense matter. To date, most studies were conducted with sub-ps laser pulses with energies of ~0.1kJ. We have used the much higher energy OMEGA EP laser at the Laboratory for Laser Energetics with a wide range of parameters (τ_L~ 0.7 – 10ps, E_L~0.1 – 1.5kJ, I_L up to 4×10^{19}W/cm^2, and with intrinsic nanoseconds prepulse energies of 0.1 – 100mJ). This allows systematical investigation of the dynamics of fast electron generation, transport and collimation resulting from self-generated magnetic fields in high intensity laser solid-target interactions from sub-ps to 10ps. Multi-layered solid foil targets used in this study are composed of an Al substrate, a Cu fluorescence layer buried ~150μm from the front surface and a thick conductive CH back layer to minimize fast electron refluxing. Fast electrons are characterized by measuring their induced Cu K-shell fluorescence and high-energy bremsstrahlung radiation. Several new findings such as the effects of laser pulse-length, contrast and transport material on fast electron beam generation and transport have been obtained: i) Laser filamentation and hosing in the extended preplasma with low-contrast pulses resulted in emission of multiple widely separated electron filaments into the solid density targets over the 10ps pulse duration as opposed to the single large beam observed with sub-ps duration; ii) High contrast pulses produced a more confined electron beam with an improved energy coupling; iii) Extending our previous resistive collimation work with sub-ps pulses [1] to 10ps pulses at higher energies, multilayered targets containing a thin (a few μm) high-resistive Au layer buried ~10μm beneath the front Al layer produced a well collimated electron beam with a spot size of ~50μm after a propagation distance of 150μm. Collisional particle-in-cell simulations using the PICLS code have been performed to model the dynamics of laser plasma interaction, fast electron generation and transport. Simulation results agree with the experimental data. These new results have important implications to fast ignition and other relativistic HED sciences.

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P.Mo_20

Self-consistent particle-in-cell modelling of short pulse absorption and transport for high energy density physics experiments

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In order to support experimental campaigns on short-pulse laser facilities, or develop point designs for fast ignition, laser interaction simulations with peak densities at, or approaching, solid density are required. Simulating high-density plasmas places severe constraints on the use of standard particle-in-cell (PIC) techniques to solve Maxwell's equations and the particle equations of motion, limiting the spatial and temporal scales which can be easily modelled. Recent increases in high performance computing (HPC) capabilities have helped to reduce the limitations on collisionless PIC simulations, but detailed modelling of collision-dominated regimes remains too computationally expensive to be performed on a regular basis. In order for detailed, collisional PIC simulations to run within a reasonable timeframe, novel approaches to modelling high-density material must be employed. For the purposes of modelling laser-plasma interactions, however, these approaches must be consistent with retaining a full PIC model in the low-density laser interaction region.

The approach proposed by Cohen, Kemp & Divol [1] has been adapted for the PIC code EPOCH. This model utilizes a ‘hybrid’ description for the plasma which replaces the standard Maxwell field solver in regions of high electron density ($\geq 100 n_c$) with a field update based on Ohm’s law. This approach relaxes the grid and time step constraints, permitting simulations to be run at a lower resolution while also dramatically reducing numerical self-heating (see figure 1).

The results of 2D simulations of short-pulse laser interactions with solid density targets will be presented. The material heating predicted by hybrid EPOCH will be compared with the result of collisionless EPOCH simulations linked to the Monte-Carlo electron transport code THOR [2].

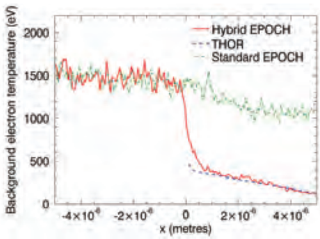

Figure 1: Lineout of the background electron temperature from obtained using ‘hybrid’ EPOCH demonstrates reduced self-heating and good agreement with THOR in the high-density transport region ($x > 0$) compared with standard EPOCH.

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P.Mo_21

Limitation of the Plasma Channel due to the Frequency Blueshift

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In laser-plasma interactions, there is a phenomenon of blueshifting of the laser pulse. The frequency blueshift has two mechanisms, which are ionization blueshift [1] and photon acceleration [2]. In addition, relativistic self-focusing is one of the important physics for laser-plasma interaction [3]. When the laser power is high enough, the laser pulse self-focuses. The plasma channel is produced in a balance between focusing and de-focusing. In plasma, the laser pulse is self-focused with frequency blueshift. The plasma channel ends when the laser power, P, becomes smaller than the critical power for self-focusing, P_{cr}. The effect of the frequency blueshift is studied in order to elucidate the plasma channel length limitation.

The experiments have been performed with a Ti:sapphire laser system. The laser pulses with 133 mJ energy are focused onto a 3-mm-diameter helium gas-jet by an off-axis parabolic mirror. The pulse width of the laser pulse is 40 fs. The estimated peak irradiances is 5.0 x 10^{17} W/cm^2. In the interaction, the laser power decreases due to the plasma generation by the laser pulse. The laser spectrum blueshifts due to (i) ionization blueshift and (ii) photon acceleration. These effects change P_{cr} and P. The plasma channel ends when $P < P_{cr}$ due to the end of the relativistic self-focusing. Figure 1 shows the relationship between P and P_{cr}. P_{cr} is calculated from the plasma density and the measured transmitted laser spectrum. When the plasma density is high enough, the plasma channel continues to the end of the gas-jet. P is in good agreement with P_{cr}. The result shows that the laser pulse in plasma is blueshifted and the plasma channel length is limited due to the spectrum shift.

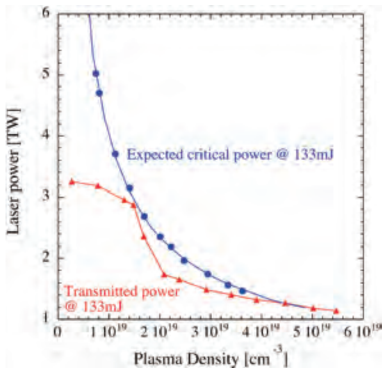

Figure 1: Relationship between the transmitted laser power and the critical power.

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P.Mo_22

Laser-plasma interaction physics for the shock-ignition conditions

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A strong shock wave driven by a high intensity laser spike ignites an imploding target in the shock ignition concept of inertial confinement fusion. The physics of laser plasma interaction under the shock ignition conditions is not sufficiently known. The laser spike intensity exceeds the threshold for parametric instabilities and collisional processes are attenuated by a relatively high plasma temperature in excess of several keV. Under these conditions strong nonlinear effects (stimulated Raman and Brillouin scattering – SRS and SBS, filamentation, two plasmon decay etc.), may reflect a fraction of the laser light and generate energetic electrons. Large scale numerical simulations with realistic parameters are necessary to calculate the laser absorption and understand the competition and coexistence of parametric processes in the interaction region.

A series of fully kinetic collisional simulations has been performed using massively parallel relativistic electromagnetic particle-in-cell codes in one-dimensional and two-dimensional geometry in the laser intensity range 1 – 40 PW/cm^2. At the lower boundary of this intensity range (a few PW/cm^2), the interaction is dominated by the collisional processes. The absorption of nearly 80% of laser pulse energy is calculated at the normal incidence, and the laser-plasma instabilities are of minor importance. At higher laser intensities (exceeding 3 – 5 PW/cm^2) the collisional processes turn over and the interaction is dominated by collective effects. The laser plasma interaction proceeds through two stages. A transient stage of the interaction of a few tens of picoseconds is characterized by a very high (80%) average reflectivity due to SBS. This stage terminates, when the efficient spatial amplification of SBS is suppressed by the plasma cavitation, which develops due to strong local fields induced by the SRS and the two-plasmon decay. The subsequent quasi-steady stage of interaction is characterized by a quite efficient absorption of about 70% due to SRS-driven plasma waves and the light trapping in the density cavities. Most of the absorbed energy goes into hot electrons with a temperature in the 20 − 40 keV range. The two-dimensional simulations reveal that the two-plasmon decay, laser beam filamentation and inflationary SRS also contribute to laser light absorption and hot electron generation at high laser intensities. The dependence of hot electron characteristics on the laser intensity and wavelength will be particularly discussed in the context of recent laser plasma interaction experiments.

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P.Mo_23

Study of shock waves generation, hot electron production and role of parametric instabilities in an intensity regime relevant for the shock ignition

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We present experimental results at intensities relevant to Shock Ignition [1] obtained at the ps Prague Asterix Laser System. We studied shock waves produced by laser-matter interaction in presence of a pre-plasma. We used two different laser beams, the first at 1ω (1300 nm) at ~ 7×10^{13} W/cm^2 to create a pre-plasma on the front side of the target, the second at 3ω (438 nm) at ~ 10^{16} W/cm^2 to create the shock wave (simulating the ignition spike).
Multilayer targets composed of 25 (or 40 μm) of plastic (doped with Chlorine), 5 μm of Copper (for K-alpha diagnostics) and 20 μm of Al for shock reference were used. To have a direct measurement of shock velocity, step targets with 10 μm of Al were used.
We changed the delay between the two beams, from 0 ps up to 1200 ps, in order to stydy pre-plasma effects on the shock wave and hot electron generation.
We used several diagnostics: x-ray spectroscopy of Chlorine, to evaluate the plasma temperature, K-alpha imaging and spectroscopy to evaluate spatial and spectral properties of the fast electrons, sho ck chronometry using a streak camera to evaluate shock velocity and shock pressure.
The study of the parametric instabilities (Stimulated Raman Scattering, Stimulated Brillouin Scattering and Two Plasmon Decay) was done taking spectra of the backscattered light, and through calorimetry to evaluate the amount of backscattered energy. The conversion efficiency into hot electrons was estimated to be ~ 0.1% and their mean energy ~ 50 KeV.
Our experimental results were simulated using two hydro codes: CHIC [2] and DUED [3-4]. Simulations reproduce the shock breakout time if we take into account the effective laser intensity on target. Due to the small focal spot, 2D effects are important and reduce the maximum ablation pressure with respect to what expected on the basis of scaling laws. This is due to lateral energy transport between the absorption region and the ablation front. The maximum pressure evaluated in our experiment (about 90 Mbar) would correspond to about 140 Mbar with "large" focal spots.

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P.Mo_24

High-intensity interaction physics for new ignition schemes

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The laser energy needed to reach ignition in Inertial Confinement Fusion can be significantly reduced by decoupling the spherical compression stage from the ignition stage. This is developed in advanced ignition schemes like Shock Ignition (SI) [1] or Fast Ignition (FI) [2]. In SI, ignition is triggered by a converging shock launched by a spike (10^{15}-3.10^{16} W/cm²) in the laser intensity. In FI, two ultra-intense pulses (≈10^{18}-10^{21} W/cm²) are used to successively create a channel in the plasma and then accelerate particles that finally ignite the compressed fuel. In the case of SI spike and of the first pulse of FI, the laser first propagates through the long (millimeter scale) and hot plasma (2-4 keV) surrounding the target at the end of the compression while being above thresholds for filamentation, Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS) and Two Plasmon Decay (TPD) [3].

The associated interaction physics has been studied with the PICO2000 facility. PICO2000 couples a short, high-intensity laser pulse (2ω 20J 1-5ps) and a long high-energy laser pulse (2ω 400J 1.5-4ns) permitting to study the interaction in the intensity range from 10^{15} up to 6.10^{18} W/cm² relevant to the interaction of the SI spike and of the first beam of FI in preformed, hot and long plasmas. The nanosecond beam fired on low-density foam targets and thin exploded foils produces millimetre scale plasmas heated to about 1 keV. Scattered powers and time-resolved spectra in forward and backward directions have been measured as a function of the laser and plasma parameters.

Regarding SI, we will present and discuss this new experiment which studied laser plasma interaction in an almost unexplored regime of intensity. A Random Phase Plate was used to control the intensity distribution in this study. The main results concern the quality of the transmitted focal spot depending on the plasma parameters and the level of backscattering.

For FI, the transmitted powers through plasmas up to two times the laser critical density were measured showing evidence of relativistic transparency. Particles accelerated along the beam axis were also measured.

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P.Mo_25

Laser-driven ablation through fast electrons in PALS experiments

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The experiments performed at Prague Asterix Laser System (PALS) were devoted to the ablation pressure formation and energy transfer into a shock wave in the solid part of a plane target irradiated by a laser pulse with intensity of I≈1-50 PW/cm^2 and duration of 200-300 ps, i.e. with the parameters corresponding to those of the laser spike designed for generating the igniting shock wave at shock ignition. The iodine laser provided a 250 ps (FWHM) pulse with an energy in the range of 100-600 J at the first (λ_1=1.315 μm) and third (λ_3=0.438 μm) harmonic frequencies. The focal spot radius of laser beam on the surface of a target made of Al or Cu was gradually decreased from 160 to 40 μm.

To study the electron density distributions and the total electron numbers in the ablative plasma at chosen instants of plasma expansion an interferometric system was used. The plasma temperature was measured via high–resolution time-integrated x–ray spectroscopy. The amount of shock wave energy was determined by measurement of a volume of the crater produced by the laser beam-target interaction. Both 2D numerical and analytical modeling with taking into account generation and transport of fast electrons were applied.

In the experiments the coupling parameter Iλ^2 was varied in the range of 10^{14} Wμm^2/cm^2 up to 8×10^{16} Wμm^2/cm^2 (low to high level of fast electrons effect). The dominant contribution of fast electron energy transfer into the ablation process and shock wave generation was found when using the first harmonic laser radiation, the focal spot radius of 40-100 μm, and the laser energy of 300-600 J. In the range of the coupling parameter of 10^{16}-8×10^{16} Wμm^2/cm^2, which corresponds to an average energy of fast electrons exceeding 50 keV, the fast electron heating results in the growth of ablation pressure from 60 Mbar at the intensity of 10 PW/cm^2 to 180 Mbar at the intensity of 50 PW/cm^2 and in the growth of the efficiency of energy conversion into the shock wave from 2 to 7 % under the conditions of 2D ablation.

P.Mo_26

Assessment of Effects on Laser Propagation From the Introduction of High-Z Dopant Into Inertial Fusion Hohlraum Plasma

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In indirect-drive inertial confinement fusion (ICF) ignition experiments on the National Ignition Facility (NIF), laser power propagation into the hohlraum interior is diminished significantly by large amounts of laser inverse-bremsstrahlung (IB) absorption into the hohlraum gas and substantial levels of stimulated Raman scattering (SRS)—typically ~17% total laser energy and as much as 40% or more of the inner beam energy. These increased levels of IB absorption and SRS are a result of hohlraum plasma temperatures being substantially lower than predicted as a consequence of processes such as dielectronic recombination in the hohlraum wall and electron thermal conductivity, that were not accounted for accurately in early models of laser absorption. In order to increase the laser power delivered to the walls, and thus increase available drive for ignition capsules, it would be desirable to decrease the losses from these effects.

Inverse bremsstrahlung losses, a consequence of ion-electron collisions, have absorption coefficient scaling as $T_e^{-3/2}$; recent work by Yin et al. [1] has shown that SRS under NIF ignition-relevant plasma conditions achieves a saturated, nonlinear, self-organized state during the fourth pulse, with SRS reflectivity scaling as $R_{\mathrm{SRS}} \sim (k\lambda_{\mathrm{De}})^{-4} \sim T_e^{-2}$ (k being the wavenumber of the electron plasma wave associated with the SRS process and λ_{De}, the Debye length). Because of the strong dependence of these processes on hohlraum plasma temperature, raising T_e by a modest amount could have a significant effect on laser power delivered.

A means by which T_e might be increased is through the introduction of trace amounts of high-Z dopant into the hohlraum gas [1,2]. One way to see this is by balancing inverse bremsstrahlung power absorption with thermal conductive losses in the plasma through which the laser propagates, obtaining an equilibrium temperature dependence on ion concentration

$$T_e \propto \left(\sum_i Z_i n_i \right)^{2/5} \left(\sum_i Z_i^2 n_i \right)^{1/5},$$

(Summations are over ionic species of density n_i.) This dependence suggests higher T_e with the introduction of high-Z dopant, e.g., Ne, which may be present at up to 0.5% under cryogenic conditions. In this presentation, rad-hydro simulations including various concentrations of high-Z dopant will be shown, along with assessment of the magnitude of the effects on R_{SRS}.

Work performed under the auspices of the U.S. Dept. of Energy by the Los Alamost National Security, LLC, Los Alamos National Laboratory.

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P.Mo_27

Laser plasma interaction experiments with combined nanosecond and picosecond laser beams

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The coupling of laser energy to Inertial Confinement Fusion targets still appears as a major issue towards ignition. The recent megajoule scale experiments performed on the NIF facility have reported huge levels of Stimulated Raman backscattering on the inner beams that were compensated for by a transfer of energy between cones at the laser entrance hole. This solution results in a spherical implosion of the fuel capsule but with a reduced amount of total energy coupled to the hohlraum. Aside of these indirect drive experiments, alternative ignition schemes are studied all around the world mainly based on direct drive compression of the fusion fuel. In this configuration, a good coupling of the low intensity compression beams to the target is expected. In contrast, the absorption of the high intensity laser beams used to trigger ignition in these advanced schemes still need further studies.

Experiments have been performed on the Pico 2000 laser facility at Ecole Polytechnique to explore laser-plasma interaction (LPI) both for indirect-drive and advanced ignition schemes. The plasmas are heated to about 1 keV by the nanosecond beam fired at 526 nm at the energy level of 400 J. The electronic density profile is adjusted with targets made of low density foams, thick foils or thin exploding foils. The interaction is studied on picosecond and nanosecond timescales in the range 10^{14}-5×10^{16} W/cm^2.

The experiments take advantage of the picosecond beam to resolve the dynamics of LPI on ps timescale, to explore LPI in the regime of higher intensity relevant to shock ignition [1] or to accelerate particles. Diagnostics are set-up on the picosecond and nanosecond beams to measure the transmitted and backscattered light. A large set of particles diagnostics have been developed to measure both their nature and energies. Our results relevant to indirect drive concern the dynamical aspects of the energy exchange between crossing beams and the growth of LPI in the presence of either hot particles or driven electrostatic waves. We will also report on the interaction in the range 5×10^{15}-5×10^{16} W/cm^2 in an exponential density profile relevant to shock ignition. In this case, the most important results concern the large level of energy backscattered by the Brillouin instability and the poor quality of the beam reaching the region of high densities.

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P.Mo_28

Feature effects on polar direct drive implosions on NIF

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Recent implosions of CH capsules using NIF's current polar direct drive (PDD) illumination geometry (N120728, N120730) show good agreement with predicted low mode symmetry simulations[1,2]. However, these experiments have revealed an interesting higher-mode equatorial feature that appeared in neither pre- nor post-shot rad-hydro simulations performed with the Hydra[3] code. This feature was exacerbated on a subsequent shot (N121207) when the upper 50° beams and the lower 44° beams were skewed around the capsule to more effectively compensate for the removal of a single quad from each of these cones for backlighting. The large intensities used for these implosions ($2x10^{15}W/cm^2$), combined with the fact that the laser beam intensity for the remaining beams in the upper 50° and the lower 44° were increased by 8/7ths, indicate that initially un-modeled effects from laser plasma instabilities (LPI) maybe responsible for producing this feature. We have recently performed simulations of these implosions including the effects of cross beam energy transfer (CBET).[4] Comparisons between the results of these simulations with and without CBET effects will be shown. How these results change with laser drive energy and beam skewing will be discussed.

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P.Mo_29

Suppressing stimulated Brillouin scattering with a chirped laser in inertial confinement fusion

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In laser-driven inertial confinement fusion(ICF), when laser irradiates plasma from ablated hohlraum or capsule, several kinds of parametric instabilities would be excited such as stimulated Brillouin scattering(SBS), stimulated Raman scattering(SRS) and filamentation, etc. These detrimental mechanisms could remarkably reduce the laser absorption or impair the implosion symmetry[1~4].

Chirped laser has a bandwidth of 5~10 nm, which has potential in detuning three-wave resonant coupling similar to the way of inhomogeneous plasma[5~9]. We have studied the interaction between the chirped laser and the plasma is studied using particle-in-cell(PIC) simulation. The result shows the not-compressed broadband chirped pulse has the ability of suppressing SBS. In single chirp case, when the laser bandwidth is much larger than the SBS growth rate($\delta\omega/\gamma_0>10$), the chirp could directly suppress the SBS, hence weaken the scattering light. In multiple chirp case, when the bandwidth is small ($\delta\omega/\gamma_0\sim 1$), the number of chirp affects SBS little. However, when the bandwidth is much larger than the growth rate($\delta\omega/\gamma_0>10$), it shows an anti-correlation between chirp number and the strength of SBS. Therefore, chirped laser, in combination with other beam-smoothing technique, could be a new potential ICF laser driver.

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Complexity and Control of Backward Stimulated Raman Scattering

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Strong laser plasma interactions are a useful test bed for exploring a rich variety of nonlinear and complex plasma phenomena. In laser fusion, big concern is related to a backward stimulated Raman scattering (BRS) on electron plasma waves (EPW) in underdense plasmas that results in a reduced coupling of laser energy to the target [1-2]. Difficulties related to a long pulse and long plasma-scale modeling and pF3D simulations of nonlinear BRS for NIF fusion targets, have been recognized [1]. Recently, efforts to reach ultra-high laser intensity at multi-exawatts and beyond, for high-energy physics are underway. At extreme laser power, where standard CPA fails, a new scheme, based on Raman-BRS amplification [3], with a counter-propagating pico-second laser pump and a femto-second resonant seed, was proposed. Still, simulations and some experiments have revealed a BRS sensitivity and a narrow parameter window to avoid parasitic instabilities (FRS, RMI, etc.) and nonlinear pulse destruction as laser pump propagates in a uniform plasma.

Firstly, we revisit the standard 3-coupled mode model of stimulated Raman back-scattering to indicate that the condition for an absolute instability [2,4], can be readily satisfied in a uniform plasma, driving a large BRS signal from a background noise. E.g., for a moderate pump, ~ 10^{14} W/cm^2, over ~ *10* microns in underdense plasma, the absolute BRS could dominate. It sets in for the interaction length-L_0 shorter than, both, the plasma length-L and absorption length-L_a; where, $L_0 = (V_e V_s)^{1/2}/\gamma_0$; γ_0 –parametric growth rate, V_e and V_s, plasma and BRS wave group velocity, respectively [2]. We point out a generic feature of the nonlinear BRS saturation which, due to a nonlinear frequency shift (EPW), instead to a steady-state through pump depletion, evolves via a quasi-periodic route to intermittent chaos, with large bursts and incoherent spectral broadening of BRS light [2,4]. Still, a fact that both, interaction and absorption length are dynamical parameters which depend on plasma evolution, contributes to an overall Raman complexity. Further, we investigate effective parameter control of the self-organized Raman regimes, including the BRS suppression to a low level, as well as, intermittent pulsations regime [4,5]. Finally, large coherent pulsation regime is proposed for an efficient ultra-short (FS) optical pulse generation by BRS in thin exploding foil plasmas [4], with the scaling investigated by analytics and particle simulations.

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P.Mo_32

1.5kT B-field by high power laser for fast-ignition laser fusion

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In fast-ignition laser fusion, it is essential to maximize an efficiency of fusion fuel heating by a relativistic electron beam generated by intense high-power laser. Large divergence angle (typically 100 deg.) of a relativistic electron beam is a critical issue to prohibit efficient heating, because energy flux of the diverged electron beam decreases significantly during transport from the generation point ton the fuel core. Active control of the beam is required to suppress the divergence angle of the relativistic electron beam. One candidate scheme is to apply an external magnetic field parallel to the beam direction in the fuel. When the magnetic flux density exceeds 2 kT, relativistic electron beam are trapped by the magnetic field lines and lateral transport of the electrons is strongly suppressed. For this purpose we use a laser-driven capacitor-coil target to generate the magnetic field instead of the conventional magnetic field generation scheme.

Figure 1 shows a microphotograph of a capacitor-coil target from the front. Two nickel disks are connected to each other with a single-turn coil made of nickel. kJ and ns laser beams are focused on the disk through the hole. Figure 2 shows the mechanism of generation of a magnetic field. A plasma is generated at driven disk, and suprathermal hot electrons with temperatures exceeding 10 keV are emitted from the plasma corona. The hot electrons stream down the electron density gradient ahead of the expanding plasma plume and impact the second disk. The second disk acquires a negative charge, and a large electrical potential develops between the disks. That potential difference drives a current in the U-turn coil. [1] 1.5 kT magnetic field pulse was measured 650 μm away from the coil by using Faraday effect. [2]

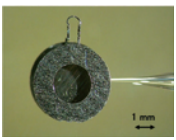

Figure 1: Laser-driven coil target.

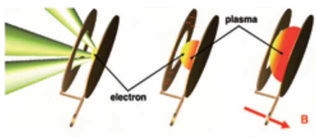

Figure 2: principle of generation of B-field.

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P.Mo_33

New Laser Fusion by NON Gamov Fusion

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This is a kind of inertial confinement fusion. But new approach of laser fusion amd their field is discussed without implosion. The cross section of nuclear reaction is increased by the enhanced penetrability of nuclei through natural Coulomb barrier. In this approach, intense laser field more than 100PW was required to distort the Coulomb barrier to obtain enough penetrability. Energy gain even with Deuterium – wdirect conversion of charged particle beam individually is proposed. Charged particles from d-d reaction are guided at the end of reactor and directly converted by a MHD scheme into electric energy. The energy recover rate is so high and required smaller laser energy, which may make this energy cost cheaper than that of a fission reactor.

Manipulating state-selective charge exchange in laser-assisted collisions of He^{2+} with atomic H

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We solve the time-dependent Schrődinger equation within a finite-differences approach and the propagation Crank-Nicolson method to calculate the n = 2, 3, and total electron capture cross section of He^{2+} colliding with atomic H in the energy collision range 0.25-35 keV. We use a Ti:Sapphire laser pulse of 10 fs at FWHM, wavelength of 800 nm and intensities of 10^{12}-10^{14} W/cm^2. We demonstrate that the laser assistance in the collision increases an order of magnitude the electron charge capture in the 0.25-2 keV energy collision range. We compare our numerical results with those obtained experimentally for the laser free case to asses the validity of our method, as shown in Fig. 1. Also, we study the effect of the laser pulse in the differential electron capture cross section and the dependence of the charge exchange in function of the laser parameters as a function of the intensity

a) b)

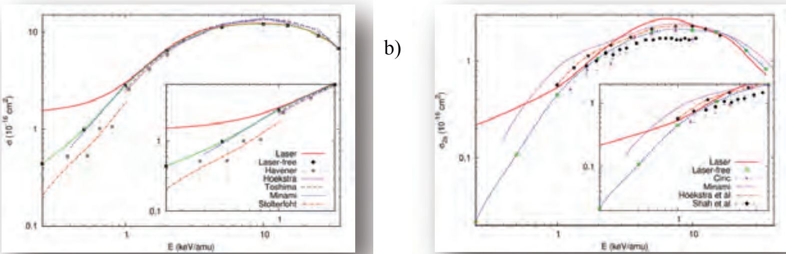

Figure 1: We show the a) total and b) 2s state electron capture cross-section for He^{2+} + H as a function of the projectile energy for both laser and laser-free cases and we compare our numerical results with some theoretical methods: Toshima [1], Stolterfoht et al. [2] and Minami et al. [3], as well as with the laser-free experimental data from Havener et al. [4], Ciric et al. [5] and Hoekstra et al. [6].

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P.Mo_35

Low-density targets that worked in direct and indirect experiments with laser and particle beams

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Solid low-density targets are widely used to have insight into some problems in the field of ICF. For decades they were proposed and studied experimentally. Here we present a review of laser experiments done with low-density targets. Mostly they were non-thermonuclear, non-standard, individually designed targets for plasma features quantitative investigations.

Experiments demonstrated not only predicted data, but also new non-expected effects. The mutual cross-check and/or verification is observed.

For a few years our experience on target development and applications was realized in the works on European drivers of LULI 2000, PALS, LIL, PHELIX, as well as on Gekko XII and OMEGA outside EU. Russian and Indian laser-target interaction experiments are considered as well.

We analyze how this pool of data enlightens some existing issues of ICF.

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P.Mo_36

Experimental Test of the Polarization Persistence in ICF

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The complete polarization of *DT* fuel would increase the fusion reactivity by 50%. For Inertial Confinement Fusion (ICF), due to the dynamics of the fusion reaction process, the fusion rate could even be higher [1]. It has been argued that the polarization would survive as well in magnetic [2] as in inertial [3] confinements. Recently, we have proposed an experiment to test the persistence of the polarization in a fusion process, using a powerful laser hitting a polarized *HD* target. The polarized *deuterons* heated in the plasma induced by the laser can fuse.

The corresponding reaction is: $D + D \rightarrow {}^3He + n$. The angular distribution of the emitted *neutrons* and the change in the corresponding total cross section are signatures to estimate the polarization persistency [4].

A proposal to test the persistence of the polarization in ICF has been accepted at the ILE: the POLAF project for (POlarization in LAser Fusion Process) [5]. It uses the polarized *HD* targets produced at the RCNP and the powerful ILE lasers, as well as the neutron detectors existing there. Both institutions are on the same campus of the Osaka University, which is favorable for the experiment.

The description of the experimental equipments will be given as well as the status of the ongoing experimental investigations.

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Polarization in Laser Fusion Process.

Ultra high temporal contrast dual-beam Ti:sapphire laser system

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Interaction of laser radiation with matter at relativistic intensity requires laser pulses with a very clean temporal shape. During the last few years considerable efforts have been devoted to increase the temporal ASE contrast of high intensity systems. These latters include the invention of the double chirped pulse amplification (DCPA) [1] architecture, that implements intermediate pulse recompression and nonlinear temporal filtering of the short pulse, investigation of nonlinear methods [2-4] required for the practical realization of a reliable DCPA, and also the development of plasma mirror technique [5], that supports substantial improvement of temporal contrast, but is currently applicable to low repetition rate systems.

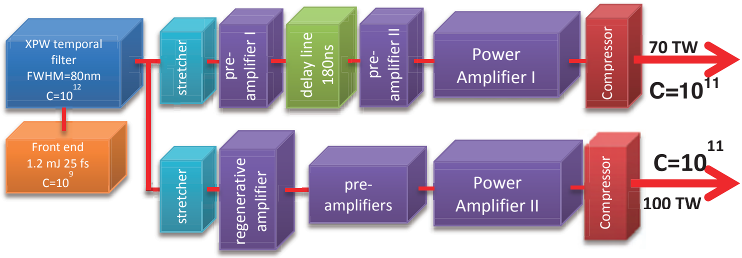

Fig.1 Block-scheme of the dual-beam DCPA laser system.

We report here on the development of a 100TW – class dual beam DCPA Ti:sapphire laser system with temporal ASE contrast above 10^{11} (in a 10 Hz operation mode). The laser systems consists of a single beam front end (the first CPA stage), a nonlinear temporal filter that uses generation of cross polarized wave (XPW) in a CaF_2 crystal [4], two parallel power Ti:sapphire CPA channels and separate compressors, one for each channel. This architecture allows for an automatic temporal link of both recompressed pulses. The front end is based on the technique of negatively and positively chirped pulse amplification (NPCPA) [6] that supports conservation of the pulse bandwidth during amplification. The nonlinear temporal filter increases the temporal contrast for 4.5 orders of magnitude and nearly doubles the pulse bandwidth is. The generated 80 nm bandwidth pulses with a contrast ratio well exceeding 10^{11} seed both arms of the laser system, so that the temporal contrast of the amplified and recompressed laser pulses for the 10Hz operation mode reaches the value of 10^{11}. Further pushing the contrast in a single shot operation mode of the installation to the level > 10^{14} can be achieved with two sets of plasma mirrors (throughput 80%) installed behind compressors.

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P.Mo_38

Conceptual Design of Sub-Exa-Watt System by Using Optical Parametric Chirped Pulse Amplification

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Ultra-high-peak-power laser system for sub-exa-watts peak power with few cycle pulse duration has been conceptually designed by using optical parametric chirped pulse amplification (OPCPA).[1] The basic concept is to generate ultra-high-peak-power pulse by shortening pulse duration. The design has been modified and changed as considering and researching. The recent status of our conceptual design is shown here.

Using benefit of OPCPA of very broad gain spectral region, our final goal is 10 fs pulse duration at 50 PW. The system has three steps in the OPCPA chain as increasing the laser pulse energy, DPSSL(diode-pumped solid-state laser)-pumped OPCPA, low-rep. glass-laser-pumped OPCPA, and single-shot glass-laser-pumped OPCPA.

Using the DPSSL-pumped OPCPA, ultra high peak power of peta-watts is expected at 100 Hz after compression. Cryogenically cooled Yb:YAG ceramics [2] are used as a laser material in the DPSSL system and large-aperture active-mirror is adopted as an amplifier scheme [2]. Those enable 100 Hz operation with 100 J pulse energy, which is frequency-doubled at 70 J as a pump source. After pulse compressor with a transmission grating pair, pulse duration will be reduced to about 500 ps. In the following OPCPA, 10 PW is expected at 0.01 Hz after compression. The split disk amplifier [3] is used with Nd:glass or Nd:YAG in the pump laser, which generates several kilo-joule pulse energy with multi beams. At the final OPCPA, a huge glass laser, which is based on our developed “LFEX” laser [4], is used. 12 kJ output power is obtained with four beams. The 8 kJ second harmonics pump the signal pulse to generate 0.05 EW peak power after pulse compressor.

In these OPCPA stages, our originally grown partially-deuterated KDP crystal will be used to obtain an optical gain over an ultra-wide spectral width of ~500 nm. There are some significant basic issues about optics. Low spectral dispersion and high optical damage threshold are required. Especially, a high reflector and a grating for the signal pulse are under discussion.

Other techniques and technologies are under developing and will be shown in the presentation.

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P.Mo_39

Development on ultra-broad band optics for high intense exa-watt laser propagation

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The appearance of high intense exa-watt laser system is useful to discover and to solve the physics of ultra-high energy density states. This kind of high intense exa-watt laser systems has been proposed by many research facilities, such as ELI (Extreme Light Infrastructure). We have also started to discuss about a high intense exa-watt laser system, Gekko-EXA, with all OPCPA amplification [1]. The target laser power is expected to be 0.1~0.2 EW (1~2 kJ of 10~20 fs pulse duration) amplified by OPCPA system from 6-fs oscillator around 1 μm (Fig.1).

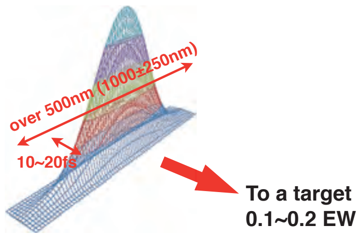

Figure 1: Target exa-watt laser pulse

In order to construct such kind of high intense exa-watt laser system, it is essential to develop ultra-broad band optics with optical window of 600-nm around 1 μm. These optics should also be requested to have well-controlled group delay dispersion in the ultra-broad propagation window with high damage threshold, however there are difficulties to fabricate the next three optics.

1) Ultra-broad band diffraction grating

As previously reported [1], the structure with HfO_2 grooves on gold substrate enables to expanding the propagation window to 500 nm with over 90 % efficiency. The problem is how to make dielectric mirror structure under the grooves to get higher damage threshold.

2) Optimized partially deuterated KDP (pKDP)

A pKDP has a possibility of ultra-broad non-linear crystal for OPCPA [2,3]. The optimum portion of exchanged deuterium is estimated to be 50~80%. We prepare several pKDP and measure the refractive index dispersion to determine the Sellmeier's dispersion formula.

3) Ultra-broad band dispersion controlled mirror (GDD of flat-negative or zero, and chirped)

In this paper, we will report on the present development status of ultra-broad band optics for high intense exa-watt laser propagation in ILE.

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P.Mo_40

A Theoretical Analysis for Laser-Induced Damage Threshold of Optical Devices at Different Temperature

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Laser-induced damage threshold of optical components for high-power laser systems is an important property to allow large output power extractable from various laser systems. Laser-induced damage mechanisms have been studied over 40 years [1]. New type of laser system is developed with cryogenic cooled Yb:YAG mediums in recent years as a high-power laser system as a next generation. The cryogenic type laser can be applied to many field, especially laser fusion [2]. The new laser system is realized with chirped-pulse amplification (CPA). In CPA, the pulse width is stretched prior to amplify the laser energy to avoid nonlinear effects. The cryogenic cooled laser system can realize high efficiency, so the output power is required higher than past high-power laser systems. Since both short and long pulses transfer in the laser systems with CPA, the understanding of pulse width dependence of laser-induced damage thresholds is essential.

In this study, temperature dependences of laser-induced damage thresholds for dielectric optical coatings were evaluated. The temperature dependence by nanosecond pulse was inversed to that by femtosecond pulse. The temperature dependences were irregular in 2-picosecond pulse. These laser-induced damage thresholds were measured with Nd:YAG laser (wavelength 1064 nm, pulse width 4 ns) and Ti:Sapphire laser (wavelength 800 nm, pulse width 200 ps, 2 ps, and 100 fs). We constructed a logical model to elucidate the temperature dependence and a laser-induced damage mechanism. The model consisted of several physical mechanisms; photoionization, electron-phonon interaction, multi-photon ionization, electron multiple, and plasma heating. The calculated results with the model agreed the laser-induced damage thresholds by femtosecond and nanosecond pulses. The calculation model would give an answer about the cause of the dependence. The irregular dependence in 2-ps pulse would also be explained when a variable expressing an influence from nonlinear phenomena was applied. The electron resistivity of optical materials is key-parameters through the modeling and discussion in this study.

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P.Mo_41

Crystal growth of pKD*P for OPCPA gain medium in Gekko-EXA

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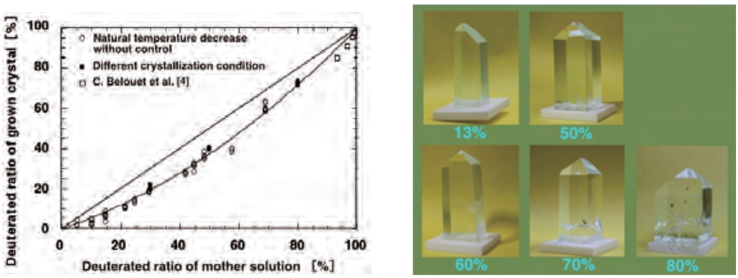
We have started to discuss about construction of a high intense exa-watt laser system, Gekko-EXA, with all OPCPA amplification [1]. The target laser power is expected to be 0.1~0.2 EW (1~2 kJ of 10~20 fs pulse duration) amplified by OPCPA system from 6-fs oscillator around 1-µm. In order to construct such a high intense exa-watt laser system, it is essential to develop ultra-broad band gain media with propagation window of 600 nm around 1-µm.

A partial deuterated potassium dihydrogen phosphate (pKD*P : $KD_{2X}H_{2(1-X)}PO_4$) has a possibility of ultra-broad gain medium for OPCPA [2,3]. The optimum portion of exchanged deuterium is estimated to be 50~80%. Therefore, we prepared several pKD*P crystals to measure the refractive index dispersions and to determine Sellmeier's dispersion formula for examining the expected gain properties. A pKD*P crystal was grown in the mixture of pure water and heavy water with KDP powder by slow cooling method and we determined the relation between deutrated ratio in a pKD*P and deuterium portion in the solution (Fig.1 (a)), then we grew desired pKD*P crystals (Fig.1 (b)). We will measure the precise refractive indices for these grown crystals.



(a) (b)

Figure 1: (a) the relation between deutrated ratio in a pKD*P and deuterium portion in the solution, (b) grown desired pKD*P crystals (13, 50, 60, 70, 80% deutrated)

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Habit control of deuterated potassium dihydrogen phosphate (DKDP) crystal for laser applications

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Large single crystals of deuterated Potassium dihydrogen phosphate (DKDP) are used for frequency conversion in high-powerful lasers. For its optimal production and to satisfy the specified requirements (i,e. size and shape), the crystal habit (referred as, aspect ratio) which is related to the growth rate of the crystallographic faces need to be controlled (See, Fig. 1). In this study, the habit of DKDP crystal (50wt% deuterium) doped with impurities (Pb^{2+}, Cr^{3+}, Al^{3+} ions) was observed in a wide range of impurity concentrations (0~100 ppm). Al^{3+}ions (2 ppm) induced to a favorable crystal growth, the crystal size increased in the Z direction compare to Pb^{2+} and Cr^{3+} ions. Then, single DKDP crystals were grown in pure (50wt% and 80wt% deuterium) and in presence of Al^{3+} (2 ppm) by the seed point technique at controlled supercooling (ΔT=10℃) condition to clarify the factors that determine the crystal habit. The aspect ratio were measured and calculated, it was found that the growth of DKDP crystal in 50wt% and 80wt% deuterium concentration were both similar in habit, while, in the presence of Al^{3+} ions, the crystals showed a relatively change in aspect ratio, the crystals size increased in the Z direction for use as optical elements at high power lasers. Finally, the characteristics of the crystals were also analyzed by X-ray diffraction, FTIR and Raman spectroscopy.

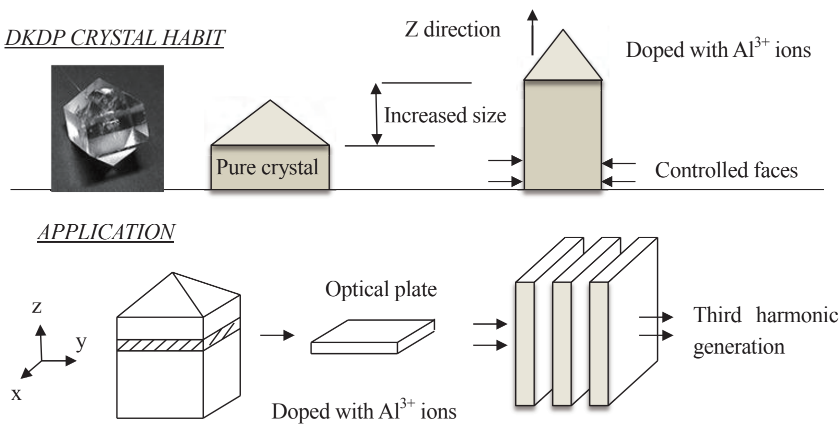

Fig. 1 Habit of pure and doped DKDP crystal and a representation of its application

P.Mo_43

Fiber CPA system delivering mJ pulse energy at repetition rate of 1-10 kHz

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There has been growing interest in the intense femtosecond pulses with durations below 10 fs for many applications like attosecond science using high-order harmonics. Ultrashort, intense laser pulses in TW region have been developed by using noncollinear optical parametric amplifier (NOPA) technique to obtain broadband amplification. We have developed a mJ-class fiber chirped pulse amplification (CPA) system as a pump source for an preamplifier stage of intense few-cycle NOPA laser. The fiber CPA system consists of laser diode (LD)-pumped single-mode fibers, a large-mode-area (LMA) fiber with a core diameter of 30 μm, and a photonic-crystal (rod) fiber with a core diameter of 100μm. The output pulse energy achieved was 1.4 mJ at a central wavelength of 1053 nm with a spectral width of 10 nm. The power fluctuation was reduced to 0.2% rms. This chirped pulse was compressed using a pair of diffraction gratings with a groove density of 1480 lines/mm. Then the pulses had an energy of 0.7mJ and a duration of 237 fs at a repetition rate of 1 kHz.

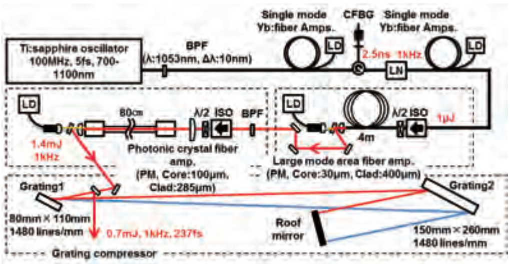

Figure 1: System layout of the all-fiber CPA system.

P.Mo_44

High-average-power nanosecond pulse laser system based on two Yb-doped rod-type PCF fiber amplifiers

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Recently, a nanosecond Yb-doped fiber systems using a DMF (Distribute Mode Filitering) fiber [1] and LPF (Large Pitch Fiber) [2] have been developed, and several hundred watts of output power was reported [3]. We have developed a high-peak and high-average-power polarization maintained Yb-doped fiber laser system based on rod-type PCF. The schematic layout of high-average-power Yb-doped fiber laser system is shown in Fig. 1. This system consists of a pulsed LD oscillator unit and a 40 μm core PCF amplifier and 100 μm core rod-type PCF amplifier, and operated at 1064 and 1070 nm, respectively.

We have developed a high-peak and high-average power Yb-doped fiber laser system, to generate a polarization-maintained pulse in PCF rod fibers. The output power per beam has been achieved to over 360W with a slope efficiency of 64 %. However, an excellent beam quality M^2 of 1.5-2 was obtained within 200 W of output power, while mode fluctuation was observed over 200 W because of thermal induced waveguide changes in PCF rod. Next, we demonstrated polarization composition of two beams. A total output power of 379W (pulse width: 10 ns, pulse energy: 1.26 mJ) at a repetition rate of 300 kHz with high beam quality was obtained with two amplifiers. Now, we are investigating the spectral (1064 and 1070 nm wavelength) and coherent combination of the amplified pulses.

A part of this work was performed under the auspices of the New Energy and Industrial Technology Development Organization (NEDO), Japan.

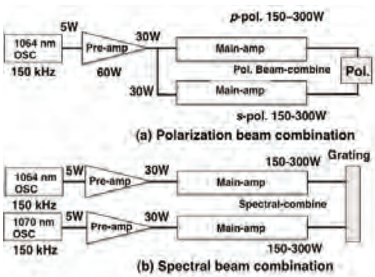

Fig.1 Schematic layout of high-peak high-average-power Yb-doped fiber laser system

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P.Mo_45

10 mW laser oscillation in 1.2 cm Nd-doped silica fiber

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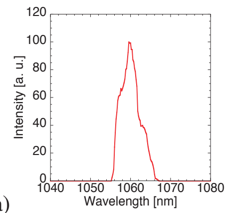
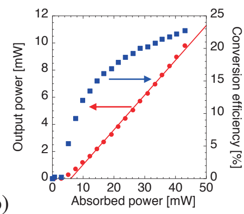
CW and pulsed lasers in a short-length rare-earth-doped silica fiber of a few centimeters has many attractive applications, such as single-frequency injection seeders, frequency comb and ultrashort pulse laser, and these lasers are expected to be used in a front-end system of a high peak power laser.

As zeolite method is effective to dope rare earth ions in silica glass homogeneously and highly, laser oscillations were successfully obtained in Nd-doped silica glass, therefore it can be helpful for short length fiber fabrication [1]. We previously reported short fiber laser oscillation in only a 1-cm-long single-mode Nd-doped silica fiber (NdSF) fabricated by zeolite method. The maximum output power and slope efficiency were 0.1 mW and 0.1%, respectively [2]. In this report, we demonstrated 10 mW laser oscillation in short-length NdSF.

In this experiment, the length, the core diameter, the V-parameter and the absorption coefficient at 810 nm of NdSF were 1.2 cm, 5.2 μm, 1.787 and 0.413 cm^{-1}, respectively. Commercial dielectric filters were closely contacted with NdSF end surfaces. The reflectivity at 1060 nm of rear and front mirrors were 99.1% and 95.0%, respectively. The output spectrum and Input-output characteristics of the NdSF laser oscillation is shown in Fig. 1. The fluorescence peak exists at 1060 nm with 6 nm bandwidth of FWHM. The maximum output power was obtained to be 9.8 mW with 6.0 mW of threshold power. The slope and optical-to-optical efficiency are calculated to be 26% and 23%, respectively. These results indicate that NdSF is useful for short fiber laser devices. Ultrashort pulse generation in such a fiber is also expected because of the wide spectra that originated from inhomogeneous broadening in silica glass [1].



(a)



(b)

Figure 1: Output spectrum (a) and input-output characteristics (b) of the 1.2-cm-lomg NdSF laser.

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P.Mo_46

Preparation of the high power laser system PETAL for experimental studies of inertial confinement fusion and high energy density states of matter

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The high power laser system PETAL (http://petal.aquitaine.fr) is sponsored by the Regional Council of Aquitaine and constructed by the CEA/CESTA, on the site of Le Barp, for academic studies of high energy density states of matter and inertial confinement fusion. It will be commissioned in 2015 and will be operated together with the Laser MegaJoule (LMJ). Significant theoretical, numerical, experimental and technical developments are still needed during the final period of PETAL construction and the starting phase of its exploitation. This period of 4 years, from 2013 to 2016 implies a tight and efficient collaboration between the scientific and technical staff of the academic groups and laboratories and the CEA engineers in order to attain in a short time scale of two years the expected laser characteristics and to assure all necessary conditions for efficient and secure operation of this unique installation. Preliminary experiments on these aspects are thus being performed on intermediate laser facilities (ECLIPSE facility at CELIA, LULI, …).

The results presented in this talk were obtained in the context of this collaboration and are related to planning and realization of the first stage of the PETAL operation so that it will be compatible with the safety requirements, the characteristics of the diagnostic equipment planned in the PETAL+ project and with the planned regular operation of PETAL together with the LMJ as an international user facility.

We will first present new results on the expected activation in the LMJ chamber induced in high power PETAL experiments by the radionuclides generated by energetic photons and protons. In the first phase of the PETAL operation, the compatibility of PETAL experiments in the context of national nuclear activity regulations has been evaluated for two regimes of operation. The characteristics of x-rays and protons originating from typical experiments that will be conducted on the PETAL laser were studied in order to estimate the activation coming from the interaction with matter of X Bremsstrahlung photons, from protons originating directly from the interaction of the laser and from the interaction of secondary particles generated after the interaction. The conclusion of this study is that the PETAL energy is limited by the chamber activation at the level of 300 J for ion radiography experiments and around 1 kJ for X-ray backlighter experiments for a pulse duration of 500 fs.

We will also present new results on the studies of strong electromagnetic fields produced during the interaction of a high intensity laser with a solid target. This effect will be of prime importance for the PETAL diagnostics. A model of the target electric polarization induced by a short and intense laser pulse is developed and verified in an experiment with a sub-picosecond laser pulse with energy of 100 mJ. It is demonstrated that this effect is responsible for generation of high amplitude GHz electromagnetic pulses in the interaction chamber.

These studies were performed in the context of the PETAL+ project funded by the Agence Nationale pour la Recherche and of the ARIEL project funded by the Conseil Régional d'Aquitaine. They were also supported by the GENCI project KITSIFI for large scale Particle-In-Cell simulations.

P.Mo_47

Enhancing NIF laser pulse shaping precision

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We discuss here two examples recently explored for enhancing the pulse shaping precision for the National Ignition Facility (NIF) [1] through improved modeling of the laser system:

The main laser section for each beam-line consists of 16 slabs of two different types of amplifying glass (Schott's LG-770 and Hoya's LHG-8). Energy and pulse shaping data are obtained at an Input Sensor Package, located just before the beams from the 48 pre-amplifiers are split four ways for injection into the 192 main beam-lines, and an Output Sensor Package located at the end of the main amplifier before the beams are transported to the final optics mounted on the target chamber wall. As the numerical propagation kernel is a Fourier beam propagator [2], the gain saturation is based on the Frantz-Nodvick (F-N) analytical solution to the rate equations as a laser pulse passes through a gain medium. In principle, there are 16 sets of two F-N parameters (small signal gain and saturation fluence for each slab) that could be used to generate a best fit to the energy output vs input curve for each beam-line, accumulated over a number of shots. We simplify this process by constraining the F-N parameters to depend only on the glass type within each beam-line. We also express both input and output energies as time dependent quantities – the partial integral of the power – enabling a full saturation curve to be extracted from each shot. The nonlinear transmission of the main laser was chosen to represent the mathematical distance between prediction and measurement because of its insensitivity to detailed pulse shape differences. Finally, different time intervals are importance-weighted based on their importance to the ignition mission, allowing us to assign a figure of merit to the overall fit achieved for each set of parameters and each shot. An experimental data set of 22 high-energy ignition-relevant shots spanning a 3 month interval illustrates that this method substantially improves the model accuracy during the initial lower-power section of the pulse while maintaining the same accuracy during the final high-powered interval.

The NIF laser system model operates under the beam propagation paradigm and therefore the interaction of the beam with each part is calculated sequentially, assuming in effect that the entire beam passes through each part before moving on to the next part in its path. In the case of an amplifier slab that is close to a cavity end mirror, however, the pulse front may pass through the slab twice before the pulse tail reaches the slab once. For ignition pulse shapes, the pulse tail carries most of the energy so this effect is benign for predicting the entire pulse energy. That model, however, can underestimate the power during the initial portion of the pulse by several percent – enough to be important to the exacting ignition pulse-shaping requirements. To introduce correction to the model that includes a feedback effect into beam propagation method we have developed a self-consistency-based algorithm with split-step gain extraction. This is enabled by the gain extraction being separable, best observed in the differential form of the F-N model. We show that for our case the lowest order term suffices, and validate that conclusion by comparison with measurements. We also derive an analytic expression for the expected enhancement of the pulse front, and compare it with numerical results.

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P.Mo_48

FM-to-AM conversion measurement for high power nanosecond lasers

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High-power nanosecond lasers like LMJ or NIF require phase modulation both for propagation purposes and for beam smoothing of the focal spot. Typical induced spectral broadenings are typically 200GHz at 1ω, and 600GHz at 3ω for LMJ. Because of any small distortion of the spectrum, part of the phase modulation is converted into unwanted amplitude modulation. This is called FM-to-AM conversion [1]. Spectral distortions may either come from smooth and stable filtering function (gain narrowing, spectral acceptance for frequency conversion...) or from interferometric filtering due to parasitic effects. Interferometric filtering may have almost any length scale ranging from μm inside coatings to meters between components. These length scales correspond to different times of flight. The longer the time of flight, the more rapidly the spectral function changes.

FM-to-AM conversion should be reduced as much as possible to avoid laser damage of the optics and changes of the optical waveform reaching the target. Hence, a lot of work has been done during the last ten years to reduce FM-to-AM conversion (by reducing spectral distortions), to reduce the sensitivity to distortions (by changing the phase modulation), and to precompensate for distortions [2]. Only smooth and stable filtering functions may be precompensated. However, to assess the improvement brought by these schemes, FM-to-AM conversion has to be measured with accuracy. Due to the very wide spectral bandwidth and the sensitivity of the phenomenon, measurement is very complicated. Measuring distortion directly in the time domain is the most secure but it requires a bandwidth that could be as high as the aforementioned spectral broadenings. Measuring the optical spectrum may seem easier but it requires a high resolution (on the order of 1 GHz) and only the spectral amplitude can be easily measured.

We have shown that FM-to-AM measurement should be done in two steps:

- first measuring the spectrum with a high resolution, for instance with a Fabry-Perot interferometer with a reduced phase modulation. This measurement will allow removing parasitic effects with long times of flight by anti-reflection coating, tilting optics...
- once the times of flight are sufficiently low, typically below 1ps (corresponding to lengths below a few hundreds micrometers), FM-to-AM conversion can be accurately measured in the time domain with an oscillator having at least 10GHz bandwidth, ideally 30GHz. This measurement can be safely used for the compensation of FM-to-AM conversion.

Further details and other results will be given during the conference.

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P.Mo_49

Cryogenic spectroscopy and energetic modeling of Yb^{3+} doped laser materials for high-energy-class diode-pumped solid-state lasers

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Diode-pumped solid-state lasers with high pulse energy, high efficiency, and good beam quality are of increasing interest for various kinds of applications, such as inertial fusion, optical parametric chirped-pulse amplification (OPCPA), and laser-accelerated particles. At present, several high-energy-class diode-pumped solid-state lasers are being developed worldwide [1 - 3] with energies of 100 J or higher based on Yb^{3+} (Yb) doped laser materials. The advantage of Yb being very low quantum defect and absence of exited state absorption and easy availability of diode lasers as pump sources and significant increase of output powers from these diode lasers.

To achieve high repetition rates (10 Hz – 20 Hz) and high output energies (1 kJ or higher) for next generation laser fusion drivers, cooling of the gain media at cryogenic temperatures is preferable [4]. Cryogenic cooling enhances not only the thermo-optic properties but also the spectroscopic properties of solid-state laser materials. This spectroscopic properties such as absorption and emission-cross sections at cryogenic temperatures are important for developing lasers of this class because these factors will help in the determination of crucial design parameters such as maximum extracted energy, small signal gain, exact pump wavelength, absorption band width etc.,

Here in this work we will describe the spectroscopic characterization of various Yb - doped laser materials namely Yb:YAG, Yb:LuAG and Yb:CaF_2 in the 80 – 340 K range [5]. We will also present a detailed analysis of the energy storage and heat deposition dependence on various pumping conditions, doping concentrations and slab sizes for the design of 100J/10 Hz Yb:YAG amplifier of the Hilase project.

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P.Mo_50

Conceptual design of 10 kW high-average power laser system based on cryogenic Yb:YAG/YAG compotsite ceramics

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Total-Reflection Active-Mirror (TRAM) configuration which consists of Yb:YAG/YAG composite ceramics was proposed to improve both thermal strength and optical damage threshold, which can be used for implementing the repeatable and high pulse energy operation [1,2]. As well as thin disk laser concept, it minimizes the temperature gradient in the laser gain medium due to the large cooling area and thin active layer. We performed fundamental thermal studies of cryogenic Yb:YAG TRAM laser to collect data for power scaling. Temperature rise, Wave-front distortion, and birefringence loss have been experimentally investigated by increasing the pump intensity up to 10 kW/cm^2 (= 500 W) in CW based on the assumption of high energy and high repetition rate laser system. We also studied amplification characteristics of TRAM laser and found that the suppression of laser gain caused by temperature rise and amplified spontaneous emission (ASE) is crucial.

In this work, we present a conceptual design of a multi-TRAMs amplifier for 10 kW-class laser system based on the experiments. Figure 1 shows a schematic design for 10 kW-class monolithic amplifier with 6 TRAMs. The thickness and Yb doping concentration of the layers were determined to satisfy the following requirements: (1) temperature rise is almost the same for all layers and is less than 15 K, (2) 100% of the pump beam will be totally absorbed. (3) the ASE gain parameter $g_0 l_{ASE}$ is set to values less than 4 to prevent the PL onset and to keep ASE at a low level. In this design, pump power of 20 kW was assumed. Numerical approaches using finite element method are utilized for theoretical investigation, and we will introduce the detail of our design.

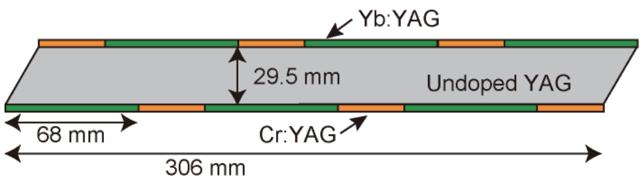

Figure 1: A conceptual design for 10 kW laser system.

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10ns/10kHz/4kW coherent beam combination laser using stimulated Brillouin scattering phase conjugate mirrors for high power 2-D processing

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For the inertial fusion energy, a laser driver that can deliver several hundred joules of energy with high repetition rate (~10Hz) is needed. It is generally hard to achieve both high-power and high-repetition rate in one laser system. The fundamental limit comes from a thermal problem of the laser media. H. J. Kong proposed a coherent beam combination laser using stimulated Brillouin scattering phase conjugate mirrors (SBS-PCMs) [1,2]. It utilizes SBS-PCM as phase conjugation device, eliminating need of complex active beam shaping elements [3]. Also, a novel concept of self phase locking locks the phases of SBS reflected waves, and the beams can be combined coherently. In recent years, beam combination using SBS-PCMs has been improved very much experimentally with 10ns/10Hz Nd:YAG laser [4].

Based on these results, the authors will construct 4kW (4 x 0.1 J @ 10 kHz) beam combination laser system. Laser diode master oscillator generates a continuous beam of 1064 nm and electro-optic modulator shapes the beam into a pulse train with a repetition rate of 10 kHz and pulse duration of 10 ns. Thorough the series of Yb-doped fiber amplifiers and Nd:YAG rod amplifiers, each pulse can generate an energy of 200 mJ at 10kJz repetition rate. A volume holographic grating split the amplified beam into 4 sub-beams and the beam combination system using SBS-PCMs recombines them into 4kW output beam. 2D laser cutting of a micro SD RAM card by using a hologram is one of the application fields of this laser.

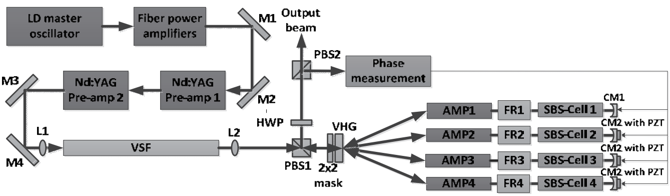

Figure 1: Proposed 4kW coherent beam combination laser system using SBS-PCMs

Acknowledgement This work was supported by Dual Use Technology Program funded by the Ministry of National Defense and National R&D Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2012-0005896), Republic of Korea.

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P.Mo_52

Remarks to SBS PCM based self-navigation of laser drivers

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A novel SBS PCM based technology of *self-navigation* of laser drivers on injected pellets was recently proposed [1]. Its feasibility as well as various implications had been gradually studied and solutions to potential problems were suggested [2, 3]. As this technology could help to overcome several burning key issues of *inertial fusion* (e.g., a sufficiently *precise navigation* of laser drivers on injected pellets in the case of a *direct-drive* scheme and *decreased requirements* on high-repetition high-power lasers) it gradually started to attract a carefully measured tentative interest among the major inertial fusion oriented laboratories and projects (e.g., HiPER). Its existence was also kindly acknowledged by major international specialists in their overview paper dedicated to inertial fusion [4].

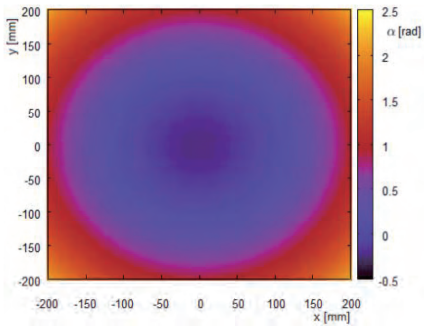

Figure 1: Phase structure for the backward reflection of the plain wave.

In this contribution we would like to report about the next step in our research which concerns the *phase* and *amplitude* structures of multiple low energy drivers illuminating the pellet after their reflection and a subsequent superposition on the collecting/focusing final optics. One example of a simple *backward* reflection of a single driver *phase* structure (of the originally *plain* wave) from a *spherical* pellet is illustrated in Fig. 1. With a large number of such drivers acting *simultaneously* from *many angles* the situation gets much more *complicated* and needs *attention*.

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P.Mo_53

Design of a serrated aperture for the tiled-aperture coherent beam combination using SBS-PCMs

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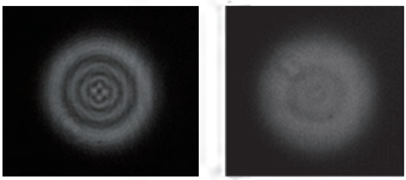
The coherent beam combination laser using SBS-PCM is the most promising technique for the high-power and high-repetition rate laser system [1]. There are two methods in coherent beam combination system, which are tiled-aperture coherent beam combination system and filled-aperture coherent beam combination system [2]. In particularly, the former divides the beam with array mask, therefore it needs spatial beam shaping to reduce the diffraction effect.

In this presentation, the authors will show the recent study of a serrated aperture. A serrated aperture has the tooth-like boundary, so it reduces the diffraction effect of the output beam. The authors calculated the laser beam profile, and research the design parameter of the serrated aperture. The parameter the authors are concerning were the length of the tooth, and the width of the tooth. As the result, the authors were calculated the condition of the parameters, and make the serrated aperture array mask. Figure 1 shows the output beam profile after the conventional circular aperture and serrated circular aperture. The detailed calculation and results will be shown during the conference.



(a) (b)

Figure 1. (a) The output beam profile after passing through the conventional circular serrated aperture and (b) the output beam profile after passing through the serrated circular aperture.

Acknowledgements. This research was supported by National R&D Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology(2012-0005896).

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Thermo-optic effects in the TGG ceramics at the high average power laser operation

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A Faraday rotator is a key component for the high energy and the high average power laser system such as a laser fusion driver, which is used for an isolation of a laser amplifier chain, a polarization control for the multi-pass amplification, and the birefringence compensation in a laser gain medium. At the operation of the high energy and the high average power laser, a magnet-optical material in the Faraday rotator is required to have high Verdet constant, high thermal strength and size scalability[1]. Terbium gallium garnet (TGG) ceramic satisfies such requirements. It has a high Verdet constant of 36 rad/Tm at the wavelength of 1 μm [2], high thermal conductivity of 4.9 W/mK, and excellent size scalability. Recently, Konoshima Chemical Co. Ltd. was successful in developing the transparent TGG ceramics for the commercial use. It can fabricate large aperture Faraday elements.

In this study, we have estimated the thermal birefringence effect and thermal lens effect by using material properties of the TGG ceramics. Main contributed properties of thermal lens effect and thermal birefringence effect are the coefficient of liner absorption a_0, incident laser power P, thermo optic coefficient Q, derivative of refractive index with respect to temperature, i.e., dn/dT, thermal conductivity κ, and thermal expansion coefficient α. We have measured α and dn/dT by the interferometric method [3], κ by the steady heat flux method, and a_0 and Q by the measurement of the laser power dependence of the depolarization ratio [4]. By using these parameters, we can estimate the laser power dependence of thermal lens and thermal birefringence effects with simple theoretical models delivered in Ref. [1]. At the average power of 1 kW, depolarization loss in TGG ceramic rod with 28 mm in length is about 3% when the flat top beam is used. Then, maximum temperature difference in the TGG ceramic rod is 2.1 K. Focal lengths of thermal lens effect are 25 m at the small aperture rod of 7mm in diameter and 5000 m at the large aperture rod of 10 cm in diameter for high energy laser to avoid laser damage.

These estimations will accelerate the development of high energy and high average power Faraday rotator and laser system for high energy and high average power laser applications.

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P.Mo_55

Characterization of liquid carbon at Mbar pressure using X-ray scattering

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The understanding of carbon at high energy density conditions is highly relevant to planetary sciences and many laboratory applications where solid state carbon samples are heated very rapidly to a dense plasma state. Very prominent examples for the latter case are inertial confinement fusion or graphite beam dumps of particle accelerators of the newest generation like the LHC. One key element hereby is the carbon solid-liquid phase transition. Although carbon is one of the most abundant elements on earth, its phase boundaries and melting properties are poorly understood at high pressures (>0.1 Mbar). Corresponding theories disagree in terms of position and slope of the melting line as well as the microscopic properties of the solid and liquid states close to the phase transition. To overcome the lack of experimental data, we successfully applied spectrally resolved X-ray scattering from shock-compressed carbon samples. Within our experiments, this method has proven to be capable of directly determining the atomic structure of carbon close to the melting region around 1 Mbar. Following this scheme, we present the first direct measurements of the microscopic structure of carbon in this regime which reliably confirms the presence of a liquid phase. This is in contrast to all previous experiments which showed only indirect indications of this phase transition by measurements recording changes in volume, reflectivity or heat capacity. In our experiments at different laser facilities, laser radiation with intensities of $\sim 10^{13}$ W/cm² compressed graphtite samples by a factor of two reaching the melting regime at temperatures of ~8000 K and pressures around 1 Mbar. Due to the melting of the crystalline structure induced by the shock, scattered signals of titanium helium-alpha (4.75 keV) or vanadium K-alpha (4.95 keV) probe radiation were modified significantly in intensity and spectral composition compared to the scattering on cold samples. It is shown that the elastic scattering on tightly bound electrons increases strongly due to the phase transition whereas the inelastic scattering on weakly bound electrons remains nearly unchanged for the chosen geometry. This can be used to constrain models of the carbon phase diagram not only by the position of the melting line but also by resulting values of the structure factor for the liquid phase.

P.Mo_56

K-shell spectroscopic diagnosis of suprathermal electrons at fusion-relevant environmental conditions

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Generation of hot electrons accompanying the high-intensity laser-matter interaction and their transport in materials with a varied degree of ionization is a subject of a fundamental research directed studies in the field of high-energy density physics but also of numerous practical applications, starting from the generation of intense bursts of energetic particles and x rays up to the direct and indirect drive inertial fusion science. Optimization of these applications requires a detailed characterization of environmental conditions and phenomena connected with the production and propagation of suprathermal electrons in the near-solid density materials.

One of the few vehicles capable of providing the desired spatially and temporally resolved information on these processes consists in a utilization of high-resolution x-ray spectroscopy. Fast electrons induce strong changes in the ion charge distribution leading to substantial modifications of radiation properties of x-ray emitting systems [1]. The sensitivity of radiative losses, spectral line intensities, ratios, and shapes (including appearance of non-diagram lines and satellites accompanying parent transitions) to non-Maxwellian electrons provide a basis for application and further development of advanced diagnostic methods of x-ray imaging spectroscopy.

The purpose of the research being performed at the Prague iodine laser system PALS is a development of the suprathermal electron diagnostics based on a detailed study of x-ray radiative properties of mid-Z elements. The experiments concentrate to the investigation of the fine spectral features introduced into the profiles of emitted x-ray lines by suprathermal electrons affecting the near-solid-density material at rather low bulk temperatures or, alternatively, dense plasma at keV temperatures. The long-scale-length plasma produced at the 1.5-μm-thick Cu foil irradiated at laser intensities up to 5×10^{16} W/cm^2 is studied by survey and high-dispersion x-ray spectrometers. We present the high resolution Cu K-shell spectra collected using the fundamental and frequency tripled laser radiation, i.e., measured at variable coupling parameters $I\lambda^2$. The spectral components corresponding to the transitions in He-like to Ne-like Cu atoms are identified, the emission of the lower-ionization-stage ions observed as a fine structure merged with the Cu Kα doublet is interpreted using collisional-radiative codes MARIA and PrismSPECT [2]. The experimentally observed spectra are analyzed with respect to the bulk plasma temperatures and hot electron fractions, the conclusions for the suprathermal electron diagnosis are drawn.

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P.Mo_57

X-ray emission spectroscopy of well-characterized, NLTE Nb and W plasmas

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Accurate calculations of multi-charged ion population dynamics in plasmas not in local thermodynamic equilibrium (NLTE) are of paramount importance for understanding and diagnosing their radiative properties. As NLTE plasmas constitute a large majority of laboratory plasmas encountered in x-ray driven fusion, x-ray laser research and laser-plasma x-ray sources, the modeling of their ionization dynamics is crucial for applications. In the past years, NLTE collisional-radiative models have widely progressed in the calculation of spectra emitted by multi-charged high-Z ions, but several discrepancies still remain. Benchmarking by well-diagnosed experiments is thus needed for the validation of such codes. The present experiment brings an important contribution to this objective, by measuring the x-ray emission of Nb and W plasmas whose hydrodynamic parameters are simultaneously measured by two additional diagnostics, namely time-resolved Thomson scattering and rear-face self-emission.

In the experiment, we irradiated Nb and W dots with the two frequency-doubled, 1.5 ns duration LULI2000 beams to reach an intensity on target of about 2 10^{14} W/cm^2. The focal spot was 400 μm in diameter so that the microdot was overfilled, producing a surrounding plastic plasma which partially tamped the lateral expansion of the Nb (or W) plasma, thus reducing the lateral gradients. A conical crystal spectrometer allowed the measurement of the Nb L-shell and W M-shell emission, in the 2.55-2.9 keV spectral range. Time-resolved Thomson scattering measured the electronic density and temperature, and the rear-face self-emission diagnostic measured the shock speed. These hydrodynamic measurements allow constraining the 1-D MULTI hydrocode. The atomic physics code FLYCHK is then used as a post-processor of the hydrodynamic code, to reproduce the experimental x-ray spectra. We are also performing calculations with the 2-D hydrocode FCI2 and with the atomic physics code AVERROES to have deeper insight in the experimental measurements. The results of these analyses will be presented.

P.Mo_58

X-ray spectroscopy of well-characterized Al and KBr plasmas, in non local thermodynamic equilibrium (NLTE) conditions

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X-ray emission of mid- to high-Z plasmas in NLTE conditions is particularly complicated to model. Benchmarking simulations is necessary, and the aim of this study is to measure NLTE emission under well-characterized hydrodynamic conditions. The issue of our experiments is to obtain independent measurements of emission and hydrodynamics parameters to constrain the hydrodynamic calculations and minimize the free parameters to be introduced in the atomic physics calculations.

We studied laser-created plasmas of KBr and Al obtained by the irradiation of solid targets (thin foils or dots). The experiment took place at the LULI2000 laser facility. We used a frequency-doubled pump beam of 1.5 ns pulse duration, focalized by means of a HPP on a 400 μm spot, at about 10^{13} W.cm^{-2} intensity on target. According to simulations, the plasmas regions observed have electronic densities of a few 10^{20} cm^{-3} and temperatures from 500 to 700 eV.

A conical crystal spectrometer recorded the X-ray emission in the 7.0 - 7.8 Å spectral range, covering some of the 2p-3d transitions in Br and the He_α and Ly_α transitions in Al. A probe beam, of the same duration as the pump beam and with variable delay, is used to probe a region of plasma at 500 μm in front of the target. This beam is used for electronic and ionic Thomson scattering time-resolved measurements, providing information on plasma electronic density and temperature. Time-resolved shadowgraphy and self optical pyrometry completed the hydrodynamic measurements, describing the expansion of the plasma and the propagation of the shock in the target.

These measurements will be compared with a previous experiment on the same elements, and with numerical calculations. First, the hydrodynamics calculations have to reproduce the hydrodynamic measurements, in order to give a reliable description of the emitting plasma evolution. Then, this description is used in atomic physics calculations to be compared to the recorded spectra.

P.Mo_59

K-shell Photoabsorption Edge Measurement in a Strongly Coupled Matter Driven by Laser-converted Radiation

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The K edge absorption measurement of high compressed warm dense matter was performed on Shenguang II laser facility [1]. The near-plank radiation, generated by laser interaction with a "Dog bone" gold hohlraum [2], were used to ablate symmetrical CH ablators to launch symmetrical inward shocks. By shielding the CH/KCl/CH sample from the laser hitting point, colliding shocks compression with low M band preheating were taken to obtain an unexplored and extreme region of the plasma state with the maximum 5 times solid density and temperature lower than 3 eV (with coupling constant Γ_{ii} around 100).

The time resolved photoabsorption spectra of chlorine near the K-shell edge were measured with a crystal spectrometer using a short x-ray backlighter. The K edge red shift up to 11.7eV and broadening of 15.2eV were obtained for the maximum compression, and then the shift and width decreased along the unloading conditions, as shown in Fig. 1.

The electron temperature inferred by Fermi-Dirac fitting of the K-edge width was consistent with the hydrodynamic predictions. The comparison of the K edge shift with a plasma model, in which the ionization effect, continuum lowering and partial degeneracy were considered, showed that more improvements were desired to describe in details the variation of K edge shift. This work is expected to extend future study of WDM matter in extreme conditions of high compression.

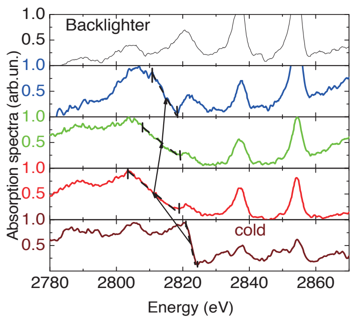

Fig.1 K edge absorption spectra at different time delays and cold K edge without heating

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P.Mo_60

First quantitative measurements of charged-particle stopping and its dependence on electron temperature in Inertial-Confinement-Fusion plasmas

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We report on the first quantitative measurements of charged-particle stopping in Inertial-Confinement-Fusion (ICF) plasmas at various conditions. In these experiments, four charged fusion products from the DD and D^3He reactions in D^3He gas-filled filled implosions were used to determine the stopping power of ICF plasmas at electron temperatures (T_e), ion temperatures (T_i), and areal densities (ρR) in the range of 0.6 – 4.0 keV, 5.4 – 11.6 keV and 1.5 – 7.5 mg/cm^2, respectively. The resulting data, in the form of measured energy downshifts of the charged fusion products, clearly indicate that the stopping-power function depends strongly on T_e (Figure 1). It was also observed that the stopping-power function is different for thin capsule-shell implosions producing mainly shock yield and thicker capsule-shell implosions producing both shock and compression yields. The most likely explanation for this is that the ions and electrons have more time to equilibrate in the thicker capsule-shell implosions, resulting in higher T_e, lower T_i and higher ρRs. In this presentation, these results will be contrasted to 1-D hydrodynamic simulations and to various stopping-power models. This work was partially supported by the US DOE and LLE National Laser User's Facility (DE-FG52-07 NA280 59 and DE-FG03-03SF22691), Laboratory for Laser Energetics (414090-G), Fusion Science Center (412761-G) and General Atomics (DE-AC52-06NA 27279).

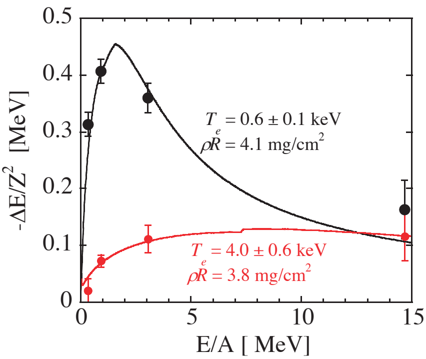

Figure 1: Measured energy loss for DD tritons, D^3He alphas, DD protons and D^3He protons in two ICF implosions at OMEGA, producing a neutron-averaged T_i of 6 keV (black) and 12 keV (red). Using the Li-Petrasso stopping-power formalism in this case [C.K. Li and R.D Petrasso, Phys. Rev. Letters 93, 3059 (1993)], a T_e of 0.6 ± 0.1 keV (black) and 4.0 ± 0.6 keV was inferred. A ρR of ~4 mg/cm^2 was inferred in both cases.

PHOTON-PLASMA INTERACTION DATA FOR NUMERICAL SIMULATION OF EXPERIMENTS ON “ISKRA-5”

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PERST code has been developed to calculate of photon absorption cross-sections in any materials. The code calculates the cross-sections of free-free absorption, bound-free absorption, bound-bound absorption and the Compton photon scattering processes. The bound-free and bound-bound absorption cross-sections are calculated for each of the higher-probability configurations of the ion state occupation numbers.

MIXER technology has been developed to calculate cross-sections in mixtures with an arbitrary composition of materials. Each atom in a mixture of elements with local thermodynamic balance is in the thermodynamic state of the same temperature, but their densities are different. In MIXER technology, the absorption cross-sections for components of a given mixture are calculated by interpolating with respect to density over the archived data and than summarize.

The plot of Rosseland free paths demonstrates oscillations at a fixed temperature and a fixed density depending on the atomic number.

The calculated mean values of Rosseland and Planck free paths are compared to the results obtained by the codes available at institutes of various countries of the world. Multigroup free paths of photons, according to the data of the PERST and MIXER technology, allow describing to an acceptable accuracy the results of spectral measurements and thermal break-down for the targets tested on “Iskra-5”.

P.Mo_62

Low energy ion beam interacting with a plasma target

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The interaction process between the energetic ion beam with a plasma target is one of the most important aspects in the study of heavy ion beam-driven high energy density physics and inertial confinement fusion [1-5]. Here the study about the proton beam in low energy regime impacting on the low density plasma target is presented.

The experiment was carried out on the 320kV highly charged ions platform at Institute of Modern Physics. The plasma was generated by igniting an electric discharge between a central high voltage electrode and two grounded electrodes situated at the entrance and exit of the discharge plasma target. The plasma temperature was about 2eV and a fully ionized hydrogen plasma could be created in the target. The electron density was varying from $2\text{x}10^{16}$ to $2\text{x}10^{17}$ cm^{-3} and the plasma life time was about 3 μs. The 1 MeV O^{5+} ions and the proton beam with the energy of 200 keV were applied to impact on the target and the outgoing ions passing through the plasma were measured using a parallel-plate and a time resolved 2D-position sensitive detector [5-6].

The charge state distribution of oxygen ions passing though the cold hydrogen gas was measured firstly. It is found that the average charge state dramatically decreases with the atomic number increasing and the equilibrium charge state is reached when the atomic number increases to a critical value.

The energy loss of proton beam passing through the cold hydrogen gas was measured too and a line function of the energy loss vs. the atomic number density is found. A Monte Carlo Mode simulation was used to calculate the variation of charge state and energy loss, and the experimental results are well coincident with the simulation results.

Then the charge state and the energy loss with the ions passing through the plasma target were measured and the differences compared to the cold gas were discussed. More details will be presented in the conference.

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P.Mo_63

Measurement of Warm Dense Matter Produced Using a Short-pulse Laser Generated Proton Beam

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The properties of warm dense matter (WDM), covering plasma conditions in the range of 0.1-10 times solid density and temperatures ~ 1-100 eV, fall between ideal plasma and condensed matter theories and have considerable uncertainties. A short-pulse laser generated proton beam can deposit energy into a sample uniformly, and on short timescales (~10 ps) compared with the time taken for significant hydrodynamic motion (isochoric heating). We describe here a methodology, previously developed at the HELEN facility [1, 2], which allowed for both time- and space-resolved measurements of the expansion of WDM generated by proton heating an aluminium wire. Analysis of high resolution streaked x-ray radiographs yielded measurements of material properties in the WDM regime. These implied initial temperatures between ~10 to 50 eV and sample densities ranging from solid to a tenth solid density as the wire expands.

Experiments are planned on the newly commissioned Orion Laser facility at AWE to study the planar expansion of Al samples. Proton heating will be driven by a short-pulse laser operating at 1054 nm firing onto gold targets. A second short-pulse laser operating at 527 nm will be used to heat a 1 μm diameter bismuth wire embedded in plastic to temperatures of 800 eV. This will produce short lived narrow band emission from the wire end which will be used to measure the expansion of the proton heated sample. Results from testing this novel point projection backlighting technique will be presented. The initial conditions and material isentropes will be determined from streaked radiographs of the expanding targets.

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P.Mo_65

Atomic processes and equation of state of high Z plasmas for EUV sources and their effect to spatial and temporal evolution of the plasmas

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Atomic processes in Sn plasmas have been intensively studied for the lithographic EUV sources. We develop a collisional radiative (CR) model of Sn, which is used to calculate the emissivity and opacity of the plasmas for the analysis of the radiation hydrodynamics to investigate the efficiency of the EUV source [1]. Development of the model has been a difficult subject due to the complex atomic structure and atomic processes in the high Z plasma, but recently accuracy of the calculation is significantly improved by the use of computational atomic data and through detailed comparisons with spectroscopic measurements as well as through the code comparison activities. Using the present atomic model one can reproduce the experimentally available fractional abundance and cooling rate of W plasmas for the condition of magnetic fusion plasmas [2]. The present model is also applicable to the studies of emission spectrum of short wavelength ($\lambda \approx 6$nm) EUV sources using plasma of rare earth elements.

Recent development of the semiconductor technology demands future EUV source to produce more than 1kW at $\lambda=13.5$nm with a conversion efficiency of 5%, which may be realized using a new concept of excitation of plasmas using a combination of ps pre-pulse and main pulse laser irradiation [3]. That requires further improvement of understanding of the plasma, especially the formation of mist or micro-particles of Sn by breaking up the Sn droplet, and subsequent interaction of the energy of the main pulse laser with the micro-particles to heat plasmas. We discuss possible modeling methods, which include the solid to gas, and gas to plasma phase transition, and take the effect to the structure formation into account, to investigate the dynamics of such plasmas.

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P.Mo_66

Atomic process modeling in dense hydrogenic plasmas by nearest neighbor approximation

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Atomic process modeling for electronic state density in dense hydrogenic plasmas is studied. In the analysis of atomic processes in plasmas, the Saha-Boltzmann relation is usually solved to obtain population of each ionic species of various electronic configurations and resulting average ionization degrees as a function of electron temperature and plasma density under the assumption that the plasmas are in the local thermodynamic equilibrium. Although the number of electronic states accounted in the model had been a big problem in doing that, I had proposed an atomic model based on the microfield in plasmas [1,2] or nearest neighbor approximation [3] to determine the reduced state density of bound state of hydrogenic ions in plasmas. For state density of free electron, state density in free space has been widely used. As for spectral calculations, state density of free electron had been adjusted alternatively instead of the reduced state density of bound electron [4]. More direct treatment of state density deformation of free electron in plasmas has not yet been considered except a few trials [5] including the Thomas-Fermi model in which electrons are treated as continuous media. In my previous papers [3], I had proposed a state density calculation of free electron based on the nearest neighbor approximation [3]. Using the models for both bound state and free state, we can calculate atomic processes in hydrogenic plasmas without any ad hoc parameters to determine the electronic state density. Since the probability of nearest neighbor ion's existence as a function of the distance between two ions had been calculated under the assumption that ions are evenly distributed in space, the models had not been applicable for dense plasmas near solid density. In this paper, we include the effect of the Coulomb interaction between the two ions within the framework of the Debye-Hückel theory, and discuss the applicability of the models for dense hydrogenic plasmas.

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P.Mo_67

Computational Package for population kinetic and radiative properties simulation of plasmas

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Fundamental research and modeling in plasma atomic physics continue to be essential for providing basic understanding of many different topics relevant to high-energy-density plasmas in a variety of conditions, mainly in the inertial and magnetic confinement fusion, laser-produced plasmas and laboratory astrophysics.

RAPCAL code determines several relevant plasma radiative properties such as the frequency dependent opacities and emissivities, mean and multigroup opacities, source functions, radiative power losses, cooling time, specific intensities and plasma transmission. The levels populations are obtained from ABAKO code which provides these one in a wide range of plasma conditions where the corona, local and non-local thermodynamic equilibrium can be achieved.

In this work we present a new computational package for modeling fusion and laboratory astrophysics plasmas and we show the new mean capabilities: non steady state, photoionized and multicomponent plasmas, a module to fit the radiative properties as a function of the density and temperature such as mean opacities and radiative power loss or cooling function, and finally, a module to analyses the radiative hydrodynamic instabilities in the context of the radiative shock waves.

P.Mo_69

A general-purpose non-LTE atomic solver for ICF and HEDP simulations

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A highly optimized and multi-material non-LTE solver has been developed to evaluate the thermodynamic and radiative properties of plasmas within large scale HEDP simulations. This fast DCA model has been implemented in parallel with the three-dimensional resistive Eulerian MHD code Gorgon[1] in order to self-consistently solve for the ion population distribution and electron temperature, simulate the emission from tens of thousands of lines whilst resolving their transition from optically thin to optically thick regime (potentially affecting the dynamics of the plasma) and generate filtered synthetic diagnostics outputs (synthetic bolometers, PCDs, etc…).

An improved offline version of this code provides a detailed post-processing treatment of line shapes and spectral features, including plasma motion Doppler, Stark, self absorption and lifetime broadening. It makes use of an original data structure devised to handle the amount of information generated by the detailed spectral treatment of the billions of numerical cells typically constituting a simulation grid.

The capabilities of the model are illustrated with inline simulations of cylindrical wire array Z-pinch experiments carried out on the Z facility at Sandia National Laboratories and SPHINX facility at CEA. The high level of spectral details provided by the offline version of the code allows us to study the time-dependant evolution of spectral line broadening and the Doppler effect of plasma motion on the apparent ion temperature for the entire simulation volume.

The significance of various non-LTE and high density plasma processes on the implosion phase of ICF capsules is assessed by coupling different opacity tables generated by the code to 3D simulations using a single group radiation transfer model.

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P.Mo_70

Fast electron beam velocity and divergence measurements and observations of intense radiation fields in petawatt-solid interactions

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Understanding the physics of intense laser driven fast electron beams, the coupling and transport of these beams in dense plasmas and solids is important to fast ignition, ion acceleration, x-ray source production and the creation of some warm dense matter states. We report on fast electron beam divergence, electron velocity distribution and radiation field [1] measurements as inferred from precision X-ray imaging and spectroscopic measurements using buried layers techniques coupled with high spatial-resolution imaging and spectroscopy of spectral resonance lines and X-ray polarization measurements. Through these measurements we can infer new aspects of the complex laser – fast electron – target interaction. The measurements were taken on Vulcan petawatt laser using high-contrast laser pulses with intensities up to 3×10 Wcm^{-2} are compared with detailed plasma and atomic physics calculations.

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P.Mo_71

Calculations of pair correlation in dense hydrogen with different models

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A Thomas-Fermi (TF) molecular dynamics code is developed and used to calculate the pair correlation for the dense strongly coupled hydrogen, by which the ion correlation effects and electron degeneracy can be considered. Meanwhile TF hypernetted chain(TFHNC) theory is also used in our calculations for comparisons. It is shown that TFHNC can reproduce the dense hydrogen pair distribution function (PDF) computed by TFMD with coupling parameter value of $\Gamma \sim 10$ in our simulations. However, when Γ increases, it is found that TFHNC fail to predict the PDF as computed by TFMD. In order to improve TFHNC model in the dense strongly coupled regime, the empirical bridge function for Yukawa systems [W. Daughton, M. S. Murillo and L. Thode, Physical Review E **61**, 129 (2000)] is adopted and incorporated in the TFHNC calculations, good agreement is obtained and presented in Fig. 2. So our improved TFHNC model could provide a more accurate approach to investigate the pair correlation for dense strongly coupled hydrogen.

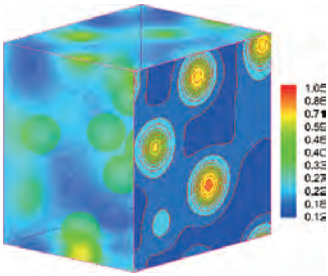

Figure 1: The electron density profile in TFMD calculations at density characterized by rs=1.0, which is electron sphere radius and normalized Bohr radius.

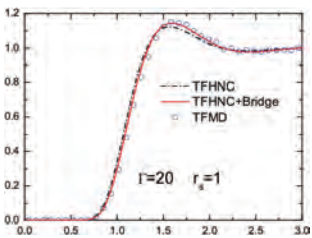

Figure 2: Computed pair correlation functions with TFHNC, TFHNC plus bridge function, and TFMD at $\Gamma = 20$ and rs=1.

P.Mo_72

Study on AC-DC Electrical Conductivities in Warm Dense Matter Generated by Pulsed-power Discharge with Isochoric Vessel

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To understand the electron behaviors in WDM, an AC electrical conductivity especially in the visible and the ultraviolet regimes should be observed. The AC electrical conductivity in those regimes gives the population of electrons in WDM, in which affects to predict the transport models. The quantitatively evaluation of AC electrical conductivity requires the DC electrical conductivity. However it is difficult to evaluate both of the electrical conductivities, experimentally. A pulsed-power discharge with isochoric vessel [1] is observed the DC electrical conductivity. To evaluate both of the electrical conductivities, we have proposed a method AC electrical conductivity measured by an ellipsometric technique [2].

For simultaneity evaluation of DC and AC electrical conductivities by using that equipment, we develop a spectroscopic ellipsometry based on a four-detector photopolarimeter. From the time-evolution of input energy, the required response of detectors is estimated to be order of a few MHz. To measure the detailed spectrum, the conventional spectroscopes are too slow due to the slower reading of charge-coupled-device (CCD) signals. On the other hand, the fast spectroscopes such as the spectroscopes mounted on the steak camera or the fast flaming ICCD is expensive. Thus, we develop the fast spectrometer based on a data logger and a plane focusing grating.

To observe the WDM emission, the spectrometers are required to be simple, controllable observation region, and fast response. Fast spectrometers, which consisted of the slit, the plane-focusing grating, 16 channels photodiode array with merging circuit as 4channels voltage adder, and a data logger, were developed[3]. The frequency response of spectrometers was evaluated. As a result, frequency response of voltage adder is plateau up to 10 MHz. To evaluate the step response of spectroscope, the time constant of spectroscope was also measured using flash lamp. As a result, the time constant of spectrometers is estimated to be 0.64 μs. It indicates that the time evolution of WDM emission is enough to observe the spectrometers.

To confirm the system, the spectroscopic ellipsometry for solid copper was demonstrated. The spectroscopic ellipsometry system is confirmed to observe the optical properties.

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P.Mo_73

Evaluation Method for Thermal Conductivity in Warm Dense Matter by using Ruby Fluorescence Probe

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Magnetic confinement fusion (MCF) such as international thermonuclear experimental reactor (ITER) and DEMO is expected to use a divertor made of tungsten, which is the highest melting temperature in the material. The tungsten divertor is exposed by the highly energetic particles from the core plasmas. On the other hand, the physics of warm dense matter (WDM) are interested in transport coefficients. In order to evaluate the transport properties in WDM, the deviation of the Lorenz number have been pointed out for dense hydrogen plasma from theoretical estimations[1] or the semi-empirical evaluation[2]. To understand the thermal conductivity, we propose an experimental observation of the thermal conductivity in dense tungsten plasma as a method of ruby fluorescence probe.

To evaluate the specific heat of dense tungsten plasma, the pulsed-power discharge technique is compatible due to the correctly evaluation of the input energy and the temperature for dense tungsten plasma. From the time-resolved spectroscopic measurements of both the sample and the ruby fluorescence, we can determine the temperature of dense tungsten plasma and that of ruby capillary. The time evolution of input power for the dense tungsten plasma is directly estimated by the input voltage and the current. Therefore, the specific heat of the dense tungsten plasma as a function of that temperature can decide the time evolution of input power.

From the estimated ruby temperature, in which is simulated by the time-dependent thermal diffusion in equation, the ruby fluorescence can be obtained from 0.5 mm to 0.6 mm. The results indicated that the ruby fluorescence probes are possible to evaluate the thermal conductivity in dense plasma.

This work was partly supported by a Grant-in-Aid for Young Scientists(B) from the Japan Society for the Promotion of Science(23740406).

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P.Mo_74

Study on Exploding Wire Compression for Evaluating Electrical Conductivity in Warm-Dense Diamond-Like-Carbon

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Critical to fast ignition is the transport of the laser-generated fast electrons and their associated heating of compressed DT fuel. The coupling efficiency of laser energy to these fast electrons and the energy deposited in the fuel should be improved the cone materials. The diamond-like-carbon (DLC)[1] cone is promised to increase the coupling efficiency due to the redaction of stopping power in cone compared to the gold cone. However, However, materials in warm dense matter (WDM) state are in a complex area where the state is neither solid, conventional fluid nor ideal plasma. We propose a method to investigate the WDM properties of insulator by using pulsed-power discharges.

The DLC WDM states are produced by exploding wire discharges with a rigid capillary [2]. The DLC membrane is coated in the capillary. The shock wave from the exploding wire is heated and compressed the DLC membrane. The material of exploding wire is gold due to the strong insulation in WDM region [3]. To control the density of exploding wire, the electrical conductivity of DLC WDM is evaluated from the voltage and current waveforms.

To evaluate the generation of DLC WDM, we have demonstrated the one-dimensional numerical simulation. The results indicated that the temperature of DLC membrane achieve 5000 K. It means that the DLC WDM is generated by the exploding wire method.

This work was partly supported by the NIFS Collaboration Research programs (NIFS13KUGK073).

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P.Mo_75

Estimation on Achievable Parameter Regime of Warm Dense Matter Generated by Isochoric Heating Discharge using Intense Pulsed Power Generator

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In inertial confinement fusion (ICF), the target consists of a fuel, an ablator, a tamper and an X-ray converter. The fuel target is rapidly imploded by irradiation of high-power laser or particle beams. As a result, the fuel becomes high density-temperature plasma at the center of the target, which generates thermonuclear reaction. The implosion uniformity is important in order to obtain sufficient the reaction. To suppress the implosion non-uniformity in ICF, a foamed metal is used for an ablator or an X-ray converter [1].

In the implosion process, especially, around solid density (10^{21}~10^{24} cm^{-3}) and the relatively low temperature (10^{3}~10^{5} K) regime is called as warm dense matter (WDM) [2]. The ablator becomes from solid to plasma through WDM during the implosion process. To understand the implosion dynamics in ICF, numerical simulations are crucial approach. The hydrodynamic behavior from the numerical simulation result depends on parameter of matter in WDM [3]. Therefore, the reliable parameter of matter is required for estimation on achievable parameter regime of WDM. However, WDM is the complex regime, because of unclear theoretical model and lacked experimental evaluations. To understand the properties of matter, an evaluation method for WDM should be established.

To generate WDM state with similar timescale of ICF implosion process, the isochoric heating discharge method [4] is applied to intense pulsed power generator ETIGO-II (~1 TW, ~50 ns) [5]. The features of the method are possible to produce isochoric condition, use of sapphire capillary, avoiding skin effect, and direct spectroscopic measurement. In previous studies, the possibility of generation WDM in the order of microsecond was established.

In this study, the achievable parameter regime of WDM generated by isochoric heating discharge method with similar timescale of ICF implosion process is estimated in ETIGO-II.

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FUNDAMENTAL SCIENCE AT THE NATIONAL IGNITION FACILITY (NIF)

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The 192-beam National Ignition Facility (NIF) at LLNL is now operating as user facility, executing state-of-the art experiments in inertial confinement fusion (ICF) and high energy density (HED) science.

NIF has made significant progress towards operation as a user facility. Through March 2013, NIF conducted over 1200 experiments in support of ICF, HED science, and development of facility capabilities. The NIF laser[1] has met or achieved all specifications and a wide variety of diagnostic[2] and target fabrication[3] capabilities are in place. Initial experiments by university users and other scientists external to the National Nuclear Security Administration (NNSA) national laboratory system have been conducted. A NIF User Group and associated Executive Board have been formed. Two successful annual User Group meetings have been conducted since formation of the User Group.

NIF experiments in fundamental science have provided important new results regarding the equation of state of carbon and iron. NIF ramp compression experiments have been conducted using diamond and iron, with EOS results obtained at pressures up to approximately 50 Mbar and 8 Mbar, respectively. Initial experiments in supernova hydrodynamics, the fundamental physics of the Rayleigh-Taylor instability, and equation of state in the Gbar pressure regime have also been conducted.

This presentation will discuss the fundamental science program at NIF, including the proposal solicitation and scientific review processes and other aspects of user facility operation. NIF infrastructure to support users will be described, and comparisons with other user facilities around the world will be made.

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P.Mo_77

Recent progress in the experimental simulations of accretion processes in magnetic cataclysmic variables: the POLAR project

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The capability to produce in laboratory radiation hydrodynamic flows relevant to high-energy astrophysical environments is a real opportunity to progress in their modeling. Recently we have proposed an original approach [1] which allows to study the radiative accretion shocks in magnetic cataclysmic variables. Using an adapted target design, we can explore, test and constrain different aspects of their physics [2]. In this work we will review the theoretical, numerical and experimental works which have been recently realized and the connection with astronomical observations.

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P.Mo_78

Collective Thomson Scattering diagnostics of Counter-Streaming Plasmas Produced by High-Power Laser Systems

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Collisionless shocks are related with many astrophysical problems, such as acceleration and generation of high-energy cosmic rays [1, 2]. For detailed researches of collisionless shocks, they have been produced in laboratories using high power laser systems [3, 4]. However, the mechanisms of collisionless shocks have not yet been understood well. For further understandings of them, measurements of plasma parameters such as electron density (n_e), electron temperature (T_e), ion temperature (T_i), and Mach number (M) are prerequisite. In order to measure such parameters with sufficient spatiotemporal resolutions, laser Thomson scattering (LTS) can be a powerful method [5, 6]. In this research, LTS has been applied to counter streaming plasmas. Under conditions of our experiment (a wavelength of a probing laser was λ=532 nm and a direction of observation of Thomson scattering was 90 degrees from the probing laser path), expected Thomson scattering spectra from these plasmas are in a collective regime. In the collective regime, Thomson scattering consists of an ion component and an electron component. In order to avoid laser perturbation due to inverse-bremsstrahlung processes, only the ion component spectra, which have relatively large intensity and would not be overwhelmed by strong plasma emission even with the small probing laser energy (< 0.3 J), were measured. For measurements of the ion component, elimination of stray light, which was generated from a target surface, was a problem since spectral widths of the ion components were narrow. To overcome this problem, a triple grating spectrometer (TGS), which has an excellent performance to eliminate stray lights, was used [7]. The experiments were performed with Gekko-XII HIPER laser at Institute of Laser Engineering, Osaka university. Double-foil Al targets (3 mm×3 mm, 0.2 mm thickness) were used to produce counter-streaming plasmas. By obtaining the ion component spectra, n_e, T_e, T_i and M were determined simultaneously. In addition, because an Intensified-CCD camera was used as a detector, one-dimensional spatially-resolved measurements were achieved at a same time.

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P.Mo_79

Material dependence of shock waves in laser-produced counter-streaming plasmas

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Physics of cosmic ray acceleration is one of the unsolved problems in astrophysics. It is speculated that cosmic rays whose energy is less than 10^{15} eV are accelerated at collisionless shocks in supernova remnants (SNRs) in our galaxy according to observation of x-rays. Therefore, collisionless shock waves are one of the most important subjects in astrophysics.

In this paper, laboratory experiment of collisionless shock waves using a high-power laser system is investigated. We focus on target material dependence of the shock wave generation. Target materials affect many plasma parameters especially ion-ion mean-free-path. In the experiment, shock waves are generated in counter-streaming plasmas irradiating one plane of parallel double-plane targets with 4.6 mm in separation. Targets are made of CH, Carbon, Al, Cu, and Pb. The experiment is performed by using Gekko XII HIPER laser system at Institute of Laser Engineering, Osaka University (the energy is ~120 J, 351 nm (3ω), pulse width is 500 ps, focal spot diameter is 300 μm, and intensity is ~2×10^{14} W/cm^2). The plasmas are diagnosed by optical diagnostics such as self-emission, shadowgraphy, and interferometry, using gated cameras and streak cameras. Collective Thomson scattering ion-component measurements are conducted using a probe laser (532 nm, < 0.3 J) and a triple grating spectrometer, which can achieve a high S/N ratio.

P.Mo_80

Thomson scattering in an unquiet plasma

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Thomson scattering has been widely used as a diagnostic technique to measure local parameters of a laboratory plasma. The spectral density function of scattered waves provides collective features as well as non-collective ones of a plasma. The collective effects become remarkable if the wavelengths of incident and scattered waves are longer than the Debye length. The measurement principle is the application of stimulated Brillouin scattering and stimulated Raman scattering of incident probe laser light. An observed scattering spectrum is fitted conventionally with the modeled spectral density function based on the assumption that the plasma is more or less quiet [1].

Recent laboratory astrophysics, on the other hand, covers highly nonlinear and non-equilibrium phenomena, e.g., collisionless shock, magnetic reconnection, etc. In such an unquiet plasma the spectral density function of scattered waves may deviate from its conventional form. However, the theoretical framework of Thomson scattering in nonlinear and non-equilibrium plasmas has not been established. In this study Thomson scattering in unquiet plasmas is investigated by using numerical simulations.

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P.Mo_81

Thomson scattering measurement of a collimated plasma jet generated by a high-power laser system

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One of the important and interesting problems in astrophysics and plasma physics is a collimation of plasma jets. The collimation mechanism, which causes a plasma flow propagates a long distance, is not understood in detail. In this report we investigate a model experiment to simulate astrophysical plasma jets, particularly the influence of the magnetic field on the collimation, by using a high-power laser system.

The experiment was performed by using Gekko XII HIPER laser system at Institute of Laser Engineering, Osaka University (energy: ~120 J/beam, 2 or 3 beams, wavelength: 351nm (3ω), pulse width: 500 ps, focal spot diameter: 300 μm, intensity: ~$2x10^{14}$ W/cm^2). We shot CH plane targets (3 mm × 3 mm × 10 μm) and observed rear-side plasma flows. A collimated plasma flow or plasma jet was generated by moving focal spots of laser beams and by applying a magnetic field perpendicular to the flow with a permanent magnet. We measured the plasma jet structures with optical diagnostics, such as self-emission, shadowgraphy, and interferometry; and simultaneously measured the local parameters of the plasma jet, i.e., electron density, electron and ion temperatures, and flow velocity, with collective Thomson scattering. An incident angle of the Thomson probe laser (wavelength: 532 nm, pulse width: ~10 ns) with respect to the HIPER laser was 45 degrees, and the scattered light was detected at 90 degrees from the probe laser by using a triple grating spectrometer.

P.Mo_82

Cosmic shocks and magnetic fields: an experiment at GEKKO

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Understanding the creation of magnetic fields in plasma shockwaves is important for explaining processes such as cosmic ray acceleration and the origin of galactic magnetic fields. As part of an on-going experimental campaign, we used the GEKKO-XII laser facility to produce shockwaves in low pressure nitrogen gas. We explored how the presence of a static background magnetic field affects the field generation mechanisms. We found that the imposition of this background field appeared to increase the magnitude of the transient shockwave-associated magnetic field.

P.Mo_83

Effect of applied magnetic field on hypersonic plasma flow generated by taper-cone-shaped plasma focus device

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Collisionless shock phenomena have unclear mechanism such as energy dissipation process and generation of highly energetic particles. In order to understand the phenomena, well-defined laboratory scale experiments are required. To generate the collisionless shock in the laboratory scale experiments, Drake, et al. [1] has considered the required conditions, which depend on the magnetic flux density and the shock velocity. To generate the collisionless shock, the hypersonic plasma flow generated by the pulsed-power system is proposed to evaluate in the laboratory scale experiment.

The hypersonic plasma flow having the shock velocity was generated by a taper-corn plasma focus system [2]. The plasma focus system consists of a pair of tapered electrodes and an acrylic guiding tube with a constant cross section, which is located on the top of the tapered electrodes. The generated shock is observed by the streak camera.

To obtain the higher shock velocity, the effects of the discharge waveform and the initial gas pressure were evaluated by the experimental observation and the numerical estimation. The piston velocity in the plasma focus was estimated by the snow-plow model. The piston velocity in the plasma focus depends on the rate of current rise. From the comparison of the experimentally obtained shock velocity and the piston velocity, the rate of current rise correspond the shock velocity. The shock velocity dependence of the initial gas pressure was evaluated. The initial gas pressure is independent of the shock velocity. It means that the pressure ratio between the disturbed and the undisturbed shocks is almost same.

The evolution of the shock wave with applied magnetic field was evaluated. The decreasing shock velocity was observed at the applied region of magnetic field. The result indicates that the magnetic pressure affects the decreasing shock velocity. We will consider the shock velocity dependence of applied magnetic field direction.

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P.Mo_84

Computational Study of Magnetic Field Amplification in Laser-Produced Shock Waves Relevant to Supernova Remnants

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High energy cosmic rays are indispensable information to understand astrophysical phenomena and are emitted from various high-energy-density events in the universe. Supernova remnant (SNR) is a typical example of the acceleration field of such cosmic rays, in which strong shocks propagate in an inhomogeneous interstellar medium. However, in the SNR environment, the acceleration of the cosmic rays requires amplification of the background magnetic field by orders of magnitude. Richtmyer-Meshkov instability (RMI), which occurs due to shock waves passing through density inhomogeneities, is considered as a cause of the field amplification because an interface extension induced by it strengthens the magnetic field [1]. Although several laboratory-astrophysics experiments relevant to the SNR environment were performed by high-power lasers [2], no clear indication of the field amplification has been found yet.

Numerical analysis is helpful to examine an evolution of the magnetic field in the laser-produced plasma flows and to design the optimal experiments. So, we newly developed a two-dimensional radiation hydrodynamics code including the magnetic field based on the laser-plasma simulation code, RAICHO [3]. The evolution of the magnetic field is estimated by the standard magneto-hydrodynamics (MHD) fashion, and the MOC-CT method [4] was installed to the original code. Numerical simulations were conducted for the experiments in which a planar plastic target was irradiated by high-power laser beams and another target was ablated by the radiation from the laser-heated target. The corresponding simulation reproduces similar shock structures to the shadowgraph obtained by the experiments, and the RMI is developed at the contact discontinuity formed by the counter flow between the targets. However, the amplified magnetic field is one-order smaller than the theoretically predicted maximum value [5]. In the full paper, we discuss a suitable configuration of the experiment for the efficient field amplification using the developed code.

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P.Mo_85

Spherical shocks in the presence of an external magnetic field

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We investigate spherical collisionless shocks in the presence of an external magnetic field. Collisionless shocks are universal phenomena in space and astrophysical plasmas, where supersonic or super Alfvénic plasma flows encounter sounding media, such as shocks in supernova remnants. A remarkable feature of collisionless shocks is the nonthermal acceleration of energetic particles or cosmic rays. It is widely believed that the cosmic rays are accelerated in the shock environments and that one of the most important factors to discuss the particle acceleration is the field orientation against the shock normal. However, it is also true that one of the most uncertain values in the astrophysical observations is the magnetic field. For instance, the relation between the field orientation and the acceleration efficiency of the cosmic rays is a long-standing and fundamental unsolved problem. So far, numerical simulations had been only ways to investigate such the problem [1-3].

Recently laboratory simulations of space and astrophysical phenomena have been actively investigated with high-power and ultra intense lasers. Collsionless shocks have been successfully created in laboratory plasmas. Shock density and emission jumps and the time evolution were obtained with optical imaging [4]. A turbulent shock electric field was observed with proton radiography [5]. Together with the global imaging, local observation of the magnetic field has demonstrated the field origin in the universe [6]. Moreover, it is also possible to measure the energy distribution functions of accelerated electrons with electron spectrometer [7, 8]. These are unique and great advantages of laboratory investigation of space and astrophysical phenomena, that is, the simultaneous observations of the global and local quantities and the energy distribution functions of particles. With these capabilities we investigate the shock propagations and the particle acceleration in the presence of a magnetic field, and their dependence on the field orientation. Furthermore, we also discuss the possibility to prove the existence of an intermediate shock, which is believed to exist in theoretical and numerical studies, however, no one has been experimentally observed it.

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P.Mo_86

Numerical studies on the nonlinear evolutions of Richtmyer-Meshkov instability in magnetized plasmas

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The Richtmyer-Meshkov instability (RMI) is of crucial importance in a variety of applications including astrophysical phenomena and laboratory experiments [1]. The RMI occurs when an incident shock strikes a corrugated contact discontinuity separating two fluids with different densities [2]. Because of the corrugation of the interface, the surface profiles of the transmitted and reflected shocks are also rippled. The RMI is driven by the vorticity left by these rippled shocks at the interface and in the fluids [3].

We have investigated the evolution of a magnetic field associated with the RMI by using two- and three-dimensional MHD simulations [4]. In terms of the field amplification, the importance of "laminar stretching" driven by the RMI at the interface is successfully demonstrated. In our single-mode analysis, an incident shock propagating through a light fluid is considered to encounter a contact surface of a heavy fluid. When the interface is spatially corrugated, the RMI takes place and a mushroom-shaped structure develops in the density profile. An ambient magnetic field is initially supposed to be uniform and subthermal. Our numerical results for various situations suggest that the RMI is an efficient mechanism of the amplification of the interstellar magnetic fields.

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P.Mo_87

Coupling between a Laser produced-plasma and external Magnetic Field up to 40 T. Applications to Astrophysical Jets

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Astrophysical jets are fascinating and ubiquitous phenomena in the Universe. These high speed, well-collimated outflows are associated with a wide range of objects such as young stellar objects (YSO), accreting stellar mass black holes or microquasars, massive black holes in active galactic nuclei (AGN) or planetary nebulae. The common model used to describe the launching, acceleration and collimation of such jets is the Blandford et Payne [1] MHD model which shows that acceleration is magneto centrifugal: the magnetic field lines are frozen-in and co-rotate with the accretion disk and matter moves along the field. However, when matter is above the Alfenic surface, the magnetic field is not large enough to make a co-rotation with the disk. The inertia of the gas causes a delay of the rotation of the magnetic field lines, which accordingly, is wound progressively and creates a toroidal component of the magnetic field. The “hoop stress” then collimates the jet. However, observations show a strong collimation of jets at long distance from the central object that cannot be explained by this mechanism. Here we explore the suggestion of Kwan et Tademaru [2] which shown that jets can be collimated by disc-associated magnetic field [3, 4]. Experimentally [5] and numerically [6], we studied the influence of a poloidal magnetic field on the evolution of a laser-produced plasma plume and compare our result with astrophysical observations. Our platform uses external magnetic field (up to 40 T) in which a high-power laser generated plasma plume is immersed. We show that close to the central object, the formation of a cavity occurs due to the competition between ram and magnetic pressure, the convergence of plasma flows towards the axis giving rise to the formation of a jet via a standing conical shock.

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P.Mo_88

Interaction Experiments with Electro-magnetically Accelerated Counter-streaming Plasma Flows

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Collisionless shocks are ubiquitous in the space and play an important role in cosmic ray acceleration. In case of electrostatic shocks, the dissipation process is acquired by the electrons trapped beyond the shock, the ion reflection and furthermore two-stream instability with the reflected ion [1]. The dissipation process leading to the shock formation depends on the situation and the plasma parameters and the structure of collisionless shock is expected to be correlated to the particle acceleration mechanism.

As an approach to study unclear mechanisms of the phenomena, not only observation using satellites and numerical simulation, but laboratory astrophysics has attracted great attention also. Although laboratory astrophysics experiments with recent high-power laser facility become hot topics [2], we developed a new type of plasma source driven by a fast pulse discharge for the formation of high-speed plasma flow [3]. A controllable, high-speed plasma with a drift velocity of ~ 30 km/s, an ion density of 10^{10-12} cm^{-3}, an electron temperature of ~ 10 eV, and a pulse length of more than few μsec was obtained using a pinching plasma in a tapered capillary. We propose a new scheme of plasma interaction experiments using a configuration of the capillary pinch device, in which a pair of tapered capillaries produce a high-speed counter-streaming plasma flow. Plasma interaction experiments at high-Mach number (M ~ 7) are possible with the counter-streaming plasma device. The plasma flux wave-forms and electron temperatures with and without the counter-streaming plasma flow were compared using Langmuir probe measurements in a wide range of parameters between a collisional to collisionless conditions.

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P.Mo_89

Magnetic flux rope structures in Weibel-mediated collisonless shock

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Laboratory experiments of collisionless shock formation have been actively carried out in high-intensity laser facilities in recent years[1]. The collisionless shock is considered to play an important role in cosmic ray acceleration observed in high-energy astrophysical phenomena, such as gamma-ray burst. The collisionless shock formation and resulting particle acceleration would originate from kinetic interactions between charged particles and electromagnetic turbulence. Three-dimensional kinetic simulations by using massive parallel computers are now leading to a considerable progress in understanding such interaction processes[2].

In order to investigate shock formation in un-magnetized plasma, we have performed large-scale three-dimensional simulations by means of a fully kinetic particle-in-cell(PIC) code. The considered situation is relevant to the laboratory experiments of shock formation using counter streaming laser-produced plasmas without ambient magnetic fields. Linear analyses and numerical simulations indicate that Weibel instability could be a dominant factor dissipating the plasma flow to form the collisionless shock in this situation[3,4]. The Weibel-mediated shock formation is essentially a multi dimensional process because unstable modes of Weibel instability propagate in a direction perpendicular to the counter streaming plasma flow.

The present simulation study demonstrates helicoid structure formation of magnetic flux rope in the dissipation region of Weibel-mediated colisionless shock. This structure is regarded as a combination of the filament and island structures, which have been demonstrated in the previous in-plane and out-of-plane PIC simulations[4], respectively. The flux rope structure becomes thicker in the downstream side of shock dissipation region through the inverse cascade of Weibel instability. Electrons tend to be confined to the thick flux rope in the downstream region while electron flow tends to be blocked in the narrower flux ropes in the upstream region. As a result of this interaction, void and filled filament structures of electron density profile are formed in the upstream and downstream regions, respectively.

We will discuss the shock dissipation mechanism associated with the flux rope structure in Weibel-mediated shock by comparing with the results of two-dimensional simulations.

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O.Mo_A9

Fast Electron Transport and Spatial Energy Deposition in Integrated Fast Ignition Experiments at the Omega Laser Facility*

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Understanding fast electron transport and spatial energy deposition in high-density plasmas is extremely important for fast ignition (FI). We have, for the first time, visualized fast electron spatial energy deposition in integrated FI experiments using Cu doped CD shells attached to the reentrant cone. This work used the high energy OMEGA laser (3 ω, 18kJ) for fuel assembly, and a high intensity OMEGA EP laser (1 ω, 10ps, E_{max}~1.5kJ, I_{peak} ~ 3×10^{19}W/cm^2) focused at the inner cone tip to produce fast electrons at various timing delays relative to the OMEGA beam, similar to previous integrated FI heating experiments [1]. Fast electron transport was characterized by imaging Cu Kα emission using a spherical crystal imager and via measuring the total Kα yield with a calibrated x-ray spectrometer. The spectra of escaped forward-going fast electrons were monitored as a function of angle by a multiple-channel magnetic spectrometer. Thermal D-D neutrons from fast electron core heating were recorded with a large liquid scintillator detector. Experiments showed an increase in the total Kα yield with EP pulse energy, with a maximum enhancement of 60% from the joint shots with 1.5 kJ EP energy compared to the implosion only case. The measured fast electron induced Kα emission region size varied with delay and was consistent with the expected size of the assembled fuel surrounding the cone tip from the 2D DRACO radiation hydrodynamic simulations [2]. More recent results showed an improved energy coupling with the high contrast EP beam (prepulse energy < 1 mJ, 100x smaller than that in the previous experiments). We simultaneously observed further enhancement in both Kα yield (up to 70% with 1.25 kJ EP energy) and D-D neutron yields (2.3×), both increasing with EP beam energy. Suppression of the forward-going electrons along the EP beam axis was also observed. The experiments are modeled using the PIC and hybrid PIC codes for fast electron generation inside the cone and transport into imploded plasma. These new findings will facilitate optimization of energy coupling with advanced target and implosion designs.

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O.Mo_A10

Efficient Generation and Collimation of Relativistic Electron Beams for Fast-Ignition Laser Fusion

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The world largest PW laser LFEX [1], which delivers energy up to 2 kJ in a 1.5 ps pulse, has been constructed beside the GEKKO XII laser. Direct-drive fast-ignition laser fusion has been intensively studied at this facility [1]. There are three potential difficulties in the fast ignition scheme, "unstoppable" , "shut-in" , and "diverging" of relativistic electron beams. Research is underway to address these difficulties.

Since relativistic electrons are scattered and stopped by Coulomb interactions and strong electric- and magnetic- fields in highly ionized high-*Z* materials (i.e. gold), a low-*Z* cone is being studied in an effort to reduce energy loss of the relativistic electrons in the cone tip region [2]. We have identified diamond-like carbon (DLC) as a potential cone material for the fast-ignition scheme [3]. It was found in a previous experiment that electron beams diverge during transport with an angle of 100 deg. [4]. Active control is required to focus the relativistic beams toward the fusion fuel. One plausible scheme is to apply an external magnetic field in parallel to the direction towards the fuel [5]. When the magnetic flux density exceeds 1 kT, relativistic electrons are trapped by the magnetic field lines and lateral transport of the electrons is strongly suppressed. We use a laser-driven capacitor-coil target [6] to generate 1 kT of the magnetic field instead of the conventional magnetic field generation scheme.

We have developed spectrometers to cover several tens keV Kα [7] line to a few MeV x-ray bremsstrahlung x rays to provide quantitative information about generation and transport of the relativistic electron beam in the fast ignition plasma [8]. The above ideas were tested with the new diagnostics.

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O.Mo_A11

Experimental evidence of enhanced resistive energy losses in high-current relativistic electron transport over warm-dense compared to cold-solid matter

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In the fast ignition of inertially confined fusion targets, a relativistic electron beam (REB) is used to ignite a compressed deuterium-tritium (DT) pellet. The energy coupling between a ~100 kJ, 10-20 ps laser beam, creating the REB, and the DT core is a key figure for the success of FI. This coupling is governed by the REB acceleration mechanisms, the REB energy losses over the standing-off distance between the electron source on a cone tip and the DT core, and the REB divergence. REB stopping power experimental characterization in warm dense matter is a challenging research field. In particular, the contribution of resistive losses in depths close to the electron source region in a FI target, where the current density is the highest, could be responsible for detrimental enhanced energy losses far from the DT core. In this context, two similar experiments were performed on the JLF-Titan laser facility (LLNL, USA). A 125 J, ~ 3×10^{20} W/cm^2, ps-laser beam was used to create a REB propagating in a multilayer target including an aluminum propagation layer, of variable thickness, and different K_α fluorescence tracer layers at both front and rear sides of the target to quantify the fraction of fast electron which cross entirely the various tested propagation layers. This propagation layer (called *sample*) was compressed (or not) by a counter propagative planar shock, rising up the aluminum density to twice the solid density and heating the material to a few eV, close to its Fermi temperature. In this geometry, collisional energy losses over the propagation layer should remain constant when comparing solid and compressed aluminum samples of the same initial thickness. A modification of the energy losses can therefore be unambiguously associated with a variation of resistive stopping power mechanisms. From hybrid simulation reproducing the experimental data, current densities $j_h = 3\times10^{11}$ A/cm^2 were reached in the propagation layer. Experimental results show that the fraction of electrons crossing the propagation layer was smaller in compressed samples compared to solid samples of initial thickness > 60 µm. This result is in agreement with preliminary estimations showing that for such current densities, resistive losses should be important enough to be experimentally detected by our method [1]. The present results are a first experimental evidence of enhanced resistive stopping power in REB transport over warm dense matter compared to cold solid sample. These results constitute a benchmarking reference for the REB transport codes and for the material resistivity modeling. A detailed numerical description using hydrodynamic PIC and hybrid codes will be presented. We will emphasize the physics of REB energy losses and extrapolate to the full-scale FI conditions.

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O.Mo_A12

DYNAMICS OF CHANNEL FORMATION IN UNDERDENSE PLASMA USING RELATIVISTIC INTENSE LASER PULSES

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ABSTRACT

The evacuation of plasma from channels formed during the interaction of intense laser pulses with under-dense plasma is attractive for a number of applications, particularly fast ignition inertial fusion. In this lecture, new experiments conducted on the Rutherford Appleton Laboratory's Vulcan Nd glass laser facility will be reported. These interactions used a 100J / 15 ps / 1054 nm laser pulse focused to an intensity of 2.5×10^{18} Wcm^{-2} on the edge of a gas-jet target. Initially solid targets were also irradiated. A comparison of channel formation with p-, s- and circular- polarisations will be presented using proton deflectometry as the diagnostic tool. In addition, the focal spot was split into two beams in the vertical plane, while the interaction probed across the horizontal plane. The separation of the spots was varied and the dynamics of the laser channels observed. Finally, a large scale-length plasma was formed by the irradiation of a target by a laser pulse comprising 100 J / 1 ns / 527 nm, focused to 400-diameter. This experiment was set-up to mimic the coronal plasma experienced during the compression phase of a directly driven implosion. The laser pulse was focused 2 mm away from the original target surface where the electron density was ~10^{18} cm^{3}. Features associated with the generation a narrow electron beam and its emergence from the back of the target will be reported. The results are supported by full-scale two-dimensional particle-in-cell simulations.

The National Ignition Facility Laser Performance Status

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The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory contains a 192-beam 4.2 MJ neodymium glass laser that is frequency converted to 351nm light or 3ω. It has been designed to support the study of Inertial Confinement Fusion (ICF) and High Energy Density Physics (HEDP).

Laser design criteria include the ability to generate pulses of up to 1.8-MJ total energy at 351nm, with peak power of 500 TW and precisely-controlled temporal pulse shapes with intensities that span two orders of magnitude. The focal spot fluence distribution of these pulses is conditioned, through a combination of continuous phase plates in the 1053 nm or 526.5nm section of the laser, smoothing by spectral dispersion, and the overlapping of multiple beams with orthogonal polarizations.

Recent facility performance achievements will be described. They include measurement capabilities and techniques to mitigate FM to AM conversion for high power operation, and increases in beam size to take full advantage of the available laser aperture. High energy and high power shots, exceeding 1.8MJ and 500TW simultaneously, will be presented to highlight this performance. The plan to implement arbitrary beam shaping capability on the NIF Programmable Spatial Shaper (PSS) systems will also be discussed.

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O.Mo_B6

Integrating the Advanced Radiographic Capability Multi-Petawatt System on the National Ignition Facility

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The National Ignition Facility (NIF)[1] at Lawrence Livermore National Laboratory is capable of producing states of matter under extreme temperature (~10^7 K) and pressure (~ GBar). This facility serves as an experimental testbed for inertial confinement fusion, planetary and stellar astrophysics, material science, advanced accelerators, etc. The NIF contains state-of-the-art diagnostics for measuring neutrons, x-rays, and gamma rays produced in these experiments. However, radiography of NIF targets require high energy x-rays above 50 keV which can be efficiently generated with high intensity laser pulses above 10^{17} W/cm^2. The Advanced Radiographic Capability (ARC)[2] currently constructed on the NIF will provide eight 1 ps to 50 ps adjustable pulses with up to 1.7 kJ each to create x-ray point sources enabling dynamic, multi-frame x-ray backlighting. ARC can also produce MeV protons and electrons for future experiments in advanced fusion, TeV acceleration and proton radiography. The system development of ARC is nearly complete and we are currently integrating the ARC laser on NIF. Subsystems were built and performance qualified in offline test bed laboratories and meet requirements. In this talk we will provide an overview of the ARC system, report on the performance testing of its subsystem and the progress of integrating ARC with NIF. Figure 1 shows the large compressor vessels currently being commissioned in the NIF target bay.

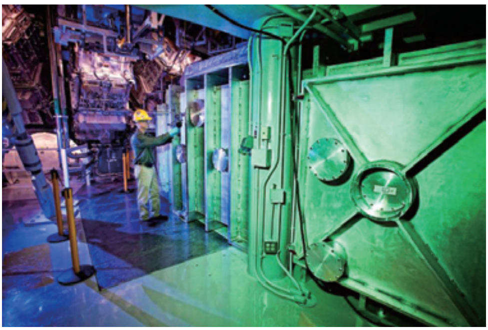

Figure 1: ARC compressor vessel next to the NIF target chamber.

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O.Mo_B7

Recent Results from the Jupiter Laser Facility

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The Jupiter Laser Facility (JLF) at LLNL is a unique capability for peer reviewed high energy density science research on materials at extreme conditions, inertial confinement fusion, and laser-plasma physics. It's mission is to support the programs of the NNSA and Office of Science through fundamental research, the development of new methods and diagnostics, and workforce development. After almost ten years of operation, JLF has contributed significantly to high pressure science, fast ignition, laser-particle acceleration, and materials research, among other fields, and is serving a community of almost 400 users. This paper will review the capabilities of the facility, including the Janus and Titan lasers, and present recent scientific results.

O.Mo_B8

Feasibility assessment of driver laser design for IFE reactor demonstration CANDY

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A CANDY is unified mini-reactor for inertial fusion energy [1]. The CANDY consists of diode-pumped laser driver, cryogenic fuel pellet with injection system and liquid Pb-Li blanket in a target chamber. A compact fast core heating scheme based on direct irradiation of heating laser pulse into the imploded core with Au cone-less target pellet is proposed in the CANDY system [2].

The CANDY equips four laser beams output from diode-pumped solid-state laser systems. Two beams are for implosion of fuel pellet and others are for heating of imploded core. Total pulse energy of four beams is 1-kJ. Repetition rate is 10Hz. Spectrum of implosion beams and heating beams are green and near infrared, respectively. Pulse shape of implosion-beams is tailored in nano-second temporal region. Pulse duration of heating-beam is 1ps. Injected cryogenic fuel pellet is implored by tailored pulses with counter-illumination. The implored core is directly heated by pico-second short pulses.

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O.Mo_C5

Reconnections of ultra-strong magnetic fields in laser produced plasmas

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Recent laser driven magnetic reconnection (LDMR) constructed with self-generated B fields has been experimentally and theoretically studied extensively [1-5], where more than Mega-Gauss strong B fields are spontaneously generated in high-power laser-plasma interactions, which located on the target surface and produced by non-parallel temperature and density gradients of expanding plasmas. For the properties of short lived and strong B fields in laser plasmas, laser driven magnetic reconnection opened up a new territory in a parameter regime not covered before. In this talk we will present the recent LDMR experimental results performed on Shenguang and Gekko laser facilities, which are aimed to understand the basic physical processes, such as particle accelerations, scale of diffusion region, and guide fields effects et al which are also strongly interested in astrophysics plasma environments.

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O.Mo_C6

Laser-plasma experimental simulations of activity of solar magnetic fields and Earth's Magnetosphere

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Reconnection of the self-generated magnetic fields in laser-plasma interaction was first investigated experimentally by Nilson et al. by shining two laser pulses a distance apart on a solid target layer [1]. An elongated current sheet (CS) was observed in the plasma between the two laser spots. In our recent laboratory investigation of magnetotail reconnection in laser plasma experiments [2,3], two side-by-side thin target layers, instead of a single one, are used. It is found that at one end of the elongated CS a fanlike electron outflow region including three well-collimated electron jets appears. This laboratory experimental observations of three electron diffusion regions (EDRs) reproduce the characteristics of Cluster satellite observations of magnetic reconnection sites at the Earth's magnetotail [4,5]. The (> 1 MeV) tail of the jet energy distribution exhibits a power-law scaling. The enhanced electron acceleration is attributed to the intense inductive electric field in the narrow electron dominated reconnection region, as well as additional acceleration as they are trapped inside the rapidly moving plasmoid formed in and ejected from the CS. The plasmoid ejection also induces a secondary CS. The experimental results then also confirm the theory and model predictions about the current-sheet-born anomalous plasmoid as the initial stage of coronal mass ejections, and the behavior of moving-away plasmoid stretching the primary reconnected field lines into a secondary current sheet conjoined with two bright ridges identified as the solar flares [6].

The effects of the driving energy of the laser pulse were also studied. The experiments present “Y-type” and “X-type” current sheets for larger and smaller driving energy, respectively [7].

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O.Mo_C7

Magnetic Turbulence in Intense-Laser-Plasmas – Observation of Kolmogorov Scaling and Transition in Turbulent Regimes

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Turbulence is ubiquitous, manifesting itself on both terrestrial and galactic scales. Turbulent flows abound in magnetized plasmas such as the interstellar media, the solar wind and the magnetosphere of the earth. Scaled laboratory simulations of these astrophysical conditions are now conceivable with the advent of intense lasers [1]. Our previous experiments [2] provide the first evidence of turbulence in laser-generated megagauss magnetic fields, characterized by a power scaling of the *k*-spectra of the magnetic fields.

Here, we report results from our recent experiments, which portray unmistakable signatures of the Kolmogorov -5/3 scaling [3] in the *k*-spectra of the turbulent magnetic fields in the highly overdense plasma (Fig. 1a). About 75 ps after the incidence of the interaction pulse, the *k*-spectrum shows a spectral kink, as shown in Fig. 1b. Similar spectral ‘knees’ have been observed previously in Alfven ion cyclotron waves in the turbulent magnetosheath of the earth [4] as well as in the transition from magnetohydrodynamic (MHD) to kinetic Alfven turbulence [5].

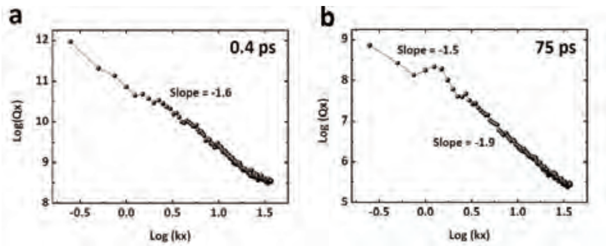

Figure 1: The *k*-spectra of the magnetic field (a) 0.4 ps and (b) 75 ps after the incidence of the interaction pulse (30 fs, 3×10^{18} W/cm^2), where $Q(k_x) = \int |B(k_x, k_y)|^2 \, dk_y$.

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O.Mo_C8

Laser-plasma experiments to study super high-energy phenomena during extreme compression of the Earth's magnetosphere by Coronal Mass Ejections.

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Problem of the global and even catastrophic modification of the Earth's magnetosphere by impulsive and huge plasma ejecta, was proposed for the first time during a study [1] of possible after-effects of high-energy explosions against asteroids at near-Earth space. Later, a similar problem [2] of extreme compression of MagnetoPause (MP) from $10R_E$ to stand-of distance R_m^*~$3R_E$, by plasma of giant Coronal Mass Ejections (CME, with energy E_0~10^{35}J [2-8]), was considered for its simulations by Laser-Produced Plasma (LPP) at KI-1 facility of ILP [4,5], that were done without "Solar Wind".

Here we present the first results of the "full" laboratory simulations of CME-MP problem with the impact of LPP into "stationary" MP (with usual radius $R_{mp} \approx 17$ cm) in a flow of H^+-Background Plasma (BP from θ-pinch type source), imitated Solar Wind under conditions of density $n_* \approx 1{,}5*10^{13}$ cm^{-3}, velocity V_*~50 km/s and parallel (to V_{*X}) uniform magnetic field $B_* \approx 20$ G. Via "Limited" Scaling Method [5] we had chose: a dipole moment $\mu_Z=5*10^5$ $G*cm^3$ and effective (for expanse into 4π) energy E_0~1000 J of directed LPP (injected with front velocity V_0~200 km/s at the X-distance R_0=46 cm from the center of dipole with radius 2,7 cm) and the following main criteria. Energetic one: $K=3E_0R_0^3/\mu^2 \sim 10^4 >> 1$; ion magnetization: $R_L/R_m^* < 1$ (for LPP's ion Larmor R_L at R_m^*); Alfven-Mach number $V/C_{A*} >> 1$ for LPP and BP; $\gamma = R_{mp}/R_m^*$. LPP was generated from plastic convex target.

In the given experiment at $\gamma=2$, with 100 ns/400 J –pulses of CO_2-laser, directed into high-vacuum target chamber ∅120 cm of KI-1, a data of magnetic and Langmuir probes, as well as framing photos, clear showed for the first time an effect of two-fold compression of MP up to new scale [1,2] of problem $R_m^* \approx 0{,}75R_0/K^{1/6} \approx 8$ cm and corresponding increase of MP internal field ~ μ_Z/R_m^3 almost in 8 times, up to $\Delta B_Z \approx 300$ G. Very important that according to R_m^*-scaling we had this ΔB_Z-value independent from μ_Z and presence of BP, when LPP was stopped at the same MP-scale (of "vacuum" case [1,2,4,5]). But at the presence of BP, some part of plasmas could penetrate up to dipole surface near its polar regions, that could be important for various dangerous effects [9] at and near the Earth.

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