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Development of an In Situ Peak Intensity Measurement Method for Ultra-intense Single Shot Laser-plasma experiments at the Sandia Z-petawatt facility

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Abstract

Using the physical process of ultra-intense field ionization of high charge states of inert gas ions, we have developed a method of peak intensity measurement at the focus of high energy short pulse lasers operating in single shot mode. The technique involves detecting ionization products created from a low pressure gas target at the laser focus via time of flight (TOF) detector. The observation of high ion charge states collected by the detector yields peak intensity at the focus when compared with the results obtained from well established tunnel ionization models. An initial peak intensity measurement of $5\ 10^{16}$ Wcm^{-2} was obtained for a 0.4 J pulse with 1 ps pulse duration focused with an *f*/5.5 off axis parabola. Experiments with multi-joule level 500 fs laser pulses are on the way.

Introduction

Peak intensity at the focus is one of the crucial parameters in high energy density physics (HEDP) experiments based on ultraintense laser solid interaction. The nature of highly non-linear coupling between the laser field and target electrons depends on the focal intensity,[1] which then determines electron transport through the target and other related mechanisms like energetic proton generation. It is also known that fast ignition inertial confinement fusion (FI-ICF) require some threshold intensity at the focus to generate fast electrons/protons.[2] It is, however, not well understood at what intensity the process is optimized. Accurate peak intensity information is also required for numerical simulation of such complex processes to explain experimental observations and guide experimental efforts.

However, to our knowledge, none of the large facilities currently operational (Vulcan at RAL, Titan at LLNL, GEKKO/FIREX in ILE, etc.) have direct intensity measurement capabilities, and intensity is estimated from indirect measurements—which involves measuring the focal spot size and determining the energy content in it, in addition to a measurement of temporal profile of the pulse with one of several autocorrelation methods. It is usually not feasible to perform the focal spot measurement with fully amplified pulse. So, a partially amplified beam is used instead (with a small percentage of its light being picked up by the front surface of a highly transmissive optic) for the measurement. With fully amplified light, more wave front distortions come to play due to the non-uniform thermal lensing effect at the gain media. The focusing element, usually an off-axis parabola (OAP), is difficult to align, and surface aberrations/imperfections may cause drastic distortion of the focal spot. Also, on the temporal profile aspect, direct pulse width measurements are not yet available for these pulses in most facilities. Indirect pulse width estimation from pulse spectrum assuming a transform limited pulse may be off by up to an order of magnitude due to imperfections in compressor gratings, or sizable accumulation of the B-integral as the ultra-short high power pulse traverse different media before arriving at the focus.[3] That is why it is in general difficult to infer *real peak intensity at the focus* from indirect measurements. So, an in situ measurement of peak intensity at the focus of an ultra-intense pulse is extremely important. In this note, we report, for the first time, the installation and preliminary experimental run of such an in situ peak intensity calibration system at the Z-petawatt laser facility at the Sandia National Laboratories.

Method

Peak intensity at the focus can be directly ascertained by observing ionization of highly charged ions at the focus. Precision measurements of high field ionization of inert gases[4, 5], with simultaneous semi-classical modeling and numerical solutions of full 3D time dependent Schrödinger's equation[6] have established the reliability of using these charge states as an effective gauge of intensity calibration at high intensities. As it was shown by Chowdhury et al.[7], semi-classical tunnel ionization rates are adequate to explain ionization of charge states (with bound energies up to a few keV's) with ultraintense lasers. In this method of determining peak intensity at the focus, usually multiple shots are required to collect enough statistics and high dynamic range. Most laser systems that are used are in the peak power range of multi-TW or less operating at 10 Hz or higher repetition rate. However, single shot intensity calibration is possible, since the probability of tunnel ionization has approximately I^5 dependence below saturation (ionization probability of 1/e), and highest peak intensity is confined to very small focal volume (e.g.

at 10^{-4} torr pressure in the 193 μm^3 (5 μm spot) volume confined by the iso-intensity surface at half peak intensity, there would be 800 Ne atoms present. At 1×10^{20} Wcm^{-2}, Ne^{9+} would have unity probability of ionization, as shown in Fig. 1. With a 50% detection efficiency (typical), 400 of these Ne^{10+} ions would be detected in a single shot), detection of highest ionization charge state of a species, and non-detection of next highest charge state essentially imposes a lower and upper bound on peak intensity, when the measurement is performed with a highly efficient detection system. Such detection systems has allowed highest dynamic range ionization yield measurements in ultra-intense fields over decades of intensity range[8]. Recent low dynamic range measurement of high charge states of Xe and Kr in JAERI 100 TW system has also demonstrated feasibility of using such a system to measure peak intensities around 10^{20} W/cm^2.[9]

Description of Experiment:
As the Z-petawatt (ZPW) laser facility is still under construction and shot accessibility is limited, our strategy involved installing two nearly identical experimental setups, one at the petawatt laser facility, and another at the Ohio State University 1 TW laser lab, where a home made 90 fs 90 mJ Ti:Sapphire laser operates at 800 nm with 10 Hz repetition rate, but also can be run at single shot mode. This way, between every few months that shots at ZPW become available, the OSU facility can act as a test bed for planning and trouble shooting experiments.

In Fig. 2, schematics of the time of flight (TOF) detector assembly setup at ZPW is shown, which is specially designed to detect highly charged ionization states of gas species. The ion detector flight tube with field plate assembly (plates 1-5 in inset of Fig. 2 are precision aligned with one another with a 500 μm diameter center hole on each) is attached to the main chamber. A leak valve delivers gas to plate 1 via an SS tubing attached to it whereas plate 2 acts as a skimmer for the gas jet. The laser focus is placed between plates 2 and 3 and aligned by crossing it with an alignment laser beam (placed at the detector end of TOF tube) coming through center holes in plates 3-5. This assembly ensures that the gas jet, laser focus and the multichannel plate (25 mm chevron MCP from Burle) detector are all aligned together. A 2-2.5 kV potential drop from plate 2 to 3 accelerates the ions past interaction region into the flight tube. The relatively high potential difference ensures minimization of space charge effects on the high charge state ion trajectories. This type of set up has been successfully used previously to collect virtually noiseless data with target gas pressures exceeding 10^{-4} torr.[8, 10] Differential pumping ensures that the detector assembly is at 10^{-8} torr (or below as the main chamber base pressure varies between 3 10^{-7} to 5 10^{-6} torr) level and the gate valve keeps it under vacuum when the main chamber is vented. The key at designing the detection setup is to set the timing of the pulsed ion selector consisting of three annular plates with wire mesh covered center-holes, where the outer plates are grounded and the center plate is attached to a high voltage pulser (DEI PVM-4210). Using a pulse generator (SRS DG 535) synchronized with the laser pulse it can block the lower ion charge states which are generated in copious amounts in the large regions surrounding the focus.

Two modes of data collection electronics were setup, one for the 10 Hz unamplified optical parametric chirp pulse amplifier (OPCPA) with 2 mJ compressed into the target chamber, and another for single shot amplified beams (400 mJ to 100 J compressed before PW compressor is constructed). Multi-shot data at low event probability (less than 0.2 ions/shot) were collected via a fast pre-amplifier (Model 9306 Ortek) to a fast timing discriminator (Model 9307 Ortek) digitizing the signal to Picosecond Time Analyzer (Model 9308 Ortek). Single shot data were collected via a 10 GHz digital oscilloscope (Tektronix). All the signal cables were shielded and collection electronics and computer placed in faraday cage to protect them from electromagnetic pulse (EMP) generated by the PW system.

Discussion and Analysis:
OSU multi shot spectrum in Fig. 3 presents nearly noise free data, even with the whole Neon outer shell stripped with 97 mJ 90 fs pulses. The chamber base pressure was 10^{-8} torr, and pressure with target gas into the chamber was 3 10^{-7} torr. The pulsed ion selector was used here to block ion charge states Ne^{+} and Ne^{2+}. The calibrated intensity by comparing ratios of theoretical ionization yields vs experimental yields results in (2.5±1.0) 10^{17} Wcm^{-2} peak intensity at the focus. Single shot measurements were also performed with the same laser observing upto Ne^{6+} consistently. Neon 7-8^{+} charges were not observed due to low event probability.

The base pressure at the Sandia target chamber was 7 10^{-6}, and with target gas into the chamber the pressure was 1.2 10^{-5} torr. The experimental run began in multishot mode with 2 mJ 10 Hz 0.5-1.0 ps OPCPA beam. A sample single shot OPCPA data is shown in Fig. 4(a) where all the Kr^{+} isotopes are present along with some background ion signals. Initially it was used to align the focus with the ion collection holes by maximizing Kr^{+} signal, and then operated in single shot mode to determine the time window and triggering offset at the oscilloscope using H^{+} and Kr^{+} ion signals. Neon could not be used because the pulse intensity was inadequate to ionize it.

The rod amplifier shot data were collected with a total of 14 shots with energies ranging from 300-400 mJ, and pulse duration of 0.5-1.0 ps within a span of two days. This was the first experimental run using the Sandia Z petawatt laser system. A few background shots were taken to compare with Neon signal which had to be delivered by a 0.25 inch bypass nozzle (connected to a makeshift gas valve) placed 1 inch away from focus, because both the gas jet and the ultrahigh vacuum leak valve were found clogged. Ions were swept away with 2.5kV potential difference between plates 2 and 3, and the MCP was biased at -1.8 kV. No pulser was used in these shots because the unit at Sandia was malfunctioning. A Sample shot TOF spectrum is shown in Fig. 4(b) with a background shot data for comparison. Compared to the OPCPA data taken with the same setup, the signal to noise ratio is much poorer. However, the clear presence of H^{+} peaks in both background and target gas shots, and various other background ion peaks helps identify neon charge states in the vicinity. Also, we note that the background peaks are wider than signal peaks and almost every background peak is suppressed in the neon spectrum due to higher target gas density. Based on the presence of the Ne^{4+} - Ne^{6+} and possibly Ne^{7+}, the peak intensity is estimated to be 5 10^{16} Wcm^{-2} with a 50% accuracy, which corresponds well with intensity estimate of 5.7 10^{16} Wcm^{-2} based on indirect method assuming the 400 mJ pulse was focused to a 30 um spot with 1 ps pulse duration.

It is clear that ion signal peaks were broken up in rod shot spectra, pointing that experimental parameters had significantly changed from that of the OPCPA shots. EMP coupling to the MCP was ruled out when it was observed that signal disappeared when the ion path to the MCP was blocked with gate valve closed. After the shots were taken, a considerable amount of thermal lensing was detected in the laser system which would cause a misalignment and degradation of the focus of the amplified beam with respect to that of the OPCPA beam. This degraded focus would create a much larger volume of lower ion charge states whose effect would worsen in the absence of a gas jet (which keeps the gas atoms confined to relatively smaller volume). The high charge states created at the center (most intense part) of this volume would then have to traverse a longer path through the charge clouds (space charge force increases linearly with radius of a uniform charge cloud), which possibly caused ion bunches to be broken up to arrive at the detector as separate sub-bunches within tens of nanoseconds, resulting in multiple peaks per charge species in the TOF spectra.

Conclusion/Future Plans:
To correct the thermal lensing in the amplifier system, adaptive optics has been installed. Shot to shot pulse duration and energy fluctuation has been minimized and the Sandia ZPW front end laser is nearly ready to fire 10-50 J amplified shots. The second phase of this experiment is expected to be arranged within a few months.

In conclusion, a new method of in situ peak intensity measurement is introduced in a large scale ultra-intense laser facility. The ion collection method is shown to operate well in multi-shot mode and single shot mode with unamplified pulse. The Sandia ZPW front end amplified laser peak focal intensity calibration has been found to be $(1.25\pm0.75)\ 10^{14}$ Wcm^{-2} per mJ energy. The reason for degradation of ion signal in amplified pulse has been identified to be an enhanced space charge effect due to the thermal lensing degradation of the target focus.

Fig. 1 Neon tunnel ionization probability in a 500 fs f/5.5 focus with 1.05 μm laser pulse.

Fig. 2 Setup of TOF assembly setup at Sandia National Laboratory target chamber. The inset shows the gas jet and field plate assembly in more details.

Fig. 3 OSU multi shot neon TOF spectrum collected with 800 nm, 90 fs pulse with 97 mJ energy into the chamber with an f/2.5 focus. Data accumulated for 22,000 shots, with chamber gas pressure of $5\ 10^{-7}$ torr.

Fig. 4. (a) Single shot ion TOF spectrum collected with 2 mJ unamplified OPCPA beam with pulse duration of 0.5-1.0 ps and a 10 μm focal spot, with Kr as sample gas. (b) Single shot ion TOF spectra (background in solid red and target gas neon in solid black) with 0.4 J pulse with pulse duration of 0.5-1.0 ps. [Total chamber pressure $1.2\ 10^{-5}$ torr with target gas for both shots (a), and (b)]

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