Probing warm-dense Silica with LCLS and betatron radiation

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Laser Wakefield Acceleration (LWFA) has been shown to produce short X-ray pulses from oscillations of electrons within the plasma wake. These betatron X-ray pulses have a broad, synchrotron-like energy spectrum and a duration on the order of the driving laser pulse, thereby enabling probing of ultrafast interactions. Using the 1 J, 40 fs short-pulse laser at the Matter in Extreme Conditions experimental station at LCLS, LWFA was implemented to generate and subsequently characterized betatron X-rays. A scintillator and a lanex screen were used to measure the charge fluence and energy spectrum of the produced electron beam.

Introduction

Silicon Dioxide, also known as Silica, is a material common in optical and electronic components. Progressing this technology requires further study of Silica's properties, specifically the reaction to optical damage. To study this process, previous researchers have conducted pump-probe studies of Silica. However, these experiments have provided limited information, due to the lack of a sufficiently short, broadband, X-ray probe. In this paper, a study of Silica is presented using a novel X-ray probe. The value of this X-ray source will be clearly defined, and diagnostic results will be presented.

Motivation

In the field of high energy density physics, studies of materials are conducted by shooting a high power laser pulse onto a target. These laser pulses ionize the target, which flies apart and is destroyed. Before the ions and electrons expand however, the energetic particles are densely packed as they would be in a solid state. This is known as warm-dense matter (WDM), and is what is seen in the center of the sun.

A common method of characterizing WDM is to follow the laser pulse with a pulse of X-rays. The X-rays pass through the target, and can measure various features of the WDM. With a sufficiently short X-ray pulse, a snapshot is taken of the developing matter. Repeating this process and varying the time between the

two pulses, a slide show can be constructed. Such a technique is known as pump-probe, as the laser pumps the target with energy and the X-ray pulse probes it.

When Silica transitions into WDM, it goes through a process known as non-thermal melting. When the laser pulse hits the Silica target, the energy is deposited into the electrons. While the electrons are energetic, the ions are still cold. As electrons transfer energy to the ions, the ionic structure begins to move from its cold state.

Previous studies of this transition have only analyzed the ion structure of warm-dense Silica. This is done with X-ray diffraction. A monochromatic source of X-rays probe the target, and are deflected at an angle which is characteristic of the spacing between ions. While this provides details of a developing ion structure, a full picture of non-thermal melting requires simultaneous measurement of electron and ion structures.

To measure electron structure, X-ray absorption spectroscopy is used. An X-ray pulse with a broad energy spectrum probes the target, exciting electrons, causing them to transition between energy levels. These transitions are caused by photons of specific energies, so by analyzing what X-ray energies were absorbed, one can determine which transitions occurred. This allows one to know what energy levels were occupied. The difficulty with doing X-ray absorption spectroscopy is that most broadband X-ray

Fig 1. The image above shows a two dimensional simulation of LWFA from YouTube user Taylor Ratliff. The laser pulse, traveling left to right, is shown blowing electrons outward. Bubbles of ions are in white, and dense packets of electrons are located at the back of the ion bubbles in red. The scale in the top left corner is the normalized electron density. Below that is the electric field of the laser. Lastly the scale on the bottom of the image is the distance the laser pulse has traveled within the plasma.

sources don't have a pulse length short enough to probe the ultra-fast transition into WDM.

Overview

At the Matter in Extreme Conditions (MEC) beam hutch at LCLS, Silica was probed using betatron radiation. Betatron radiation is a short pulse of X-rays produced in a laser-matter interaction known as Laser Wakefield Acceleration (LWFA). LWFA occurs when a laser pulse travels through a plasma, pushing electrons out radially from the laser axis. These electrons experience an attractive force back inwards due to the positively charged ions left in their absence. The electrons travel back to the laser axis, overshoot, and continue to expand and retract. This results in bubbles of positive charge trailing behind the laser pulse with sheaths of electrons surrounding them.

Some of these electrons get trapped in the laser axis and are dragged behind the laser pulse due to the force from the ion

bubbles. These electrons are accelerated to relativistic speeds and ejected from the target. The short distance needed to accelerate the electrons to high energies makes LWFA an attractive form of particle acceleration.

Not all of the laser's energy is deposited in the electron beam however; some energy is lost to radiation. As the electrons are accelerating forward through the wake, they experience small, radial oscillations. These oscillations produce X-rays, which are emitted in the forward direction, in a narrow beam. Due to the nature of their creation, the X-rays are emitted in a pulse with a duration on the same order as the laser pulse which produced the wake. These X-rays are broadband, synchrotron-like spectrum, which is characterized as having an exponentially decreasing tail. By focusing this radiation, the betatron pulse can be used to perform absorption spectroscopy on ultra-fast transitions.

To produce the betatron radiation, a gas cell was used. This gas cell functioned as the medium for LWFA. When the laser was shot, a trigger released a puff of nitrogen doped helium. By doping the helium with nitrogen, the production of accelerated electrons is increased. As the ionization energy for nitrogen is greater than helium, some electrons are ionized within the wake by the more intense portion of the laser pulse. This increases the electrons' likelihood to be accelerated, maximizing the betatron production.

To drive the betatron radiation, an 800 nanometer, Ti-Sapphire laser was used. The laser pulse contains 1 Joule of energy with a 40 femtosecond pulse length and was focused using an off axis parabola. A portion of the pulse is removed to pump the Silica target. Additionally, part of the pulse is also removed to probe the gas cell. The gas cell probe passes through a window on the side of the gas cell, and is delivered to an interferometer. The portion of the gas cell which is ionized has a

different index of refraction. This difference means that the portion of the beam will travel at a different speed from the rest. This results in a shift of phase in the laser. The interferometer takes in the phase shifted portion of the pulse, overlays it with a reference portion, producing fringes as a result of interference between the two. The spacing between the fringes can be measured to determine the index of refraction and thereby the density of the plasma.

From the gas cell, the laser pulse comes out followed by an electron beam and the betatron pulse. The electrons are bent by a magnet, and run into a block of lead. The photons, being without charge, pass through the magnet undeterred. From there, they pass through a filter, which selectively removes 800 nanometer wavelengths. This removes most of the laser pulse, and leaves most of the betatron radiation untouched. The betatron pulse is then focused onto the target with an ellipsoidal mirror.

Fig 2. Above is a diagram of the experimental setup.

Fig 3. Scintillator data from three days of shots. These figures show variation in electron production as a result of changing gas cell parameters such as Nitrogen percentage, gas pressure, and focus of laser within the cell. The saturation limit can be seen at around 6 volts.

To control the timing of the system, delay stages were implemented. These delay stages consist of two mirrors with faces angled 90 degrees from one another. A beam is reflected off one mirror, then off the other, sending the beam back parallel to its initial path. By placing the mirrors on a translation stage, the path length can be tailored. The timing between the laser and the LCLS X-ray pulse can be controlled, allowing the two X-ray probes to be synchronized. The timing between the target pump and the probes can then be controlled with one delay stage. An additional delay stage is used to synchronize the gas cell pump and probe.

Results

To remove room for error, diagnostics were implemented to detect electrons. With such an intricate system, there are several possible sources for a loss of betatron signal. For this reason, detecting electrons allow experimenters to determine the problem faster.

One such diagnostic used was a scintillator. This scintillator was attached to the outside of the target chamber, where it detected the radiation produced when the electrons hit the lead block and rapidly slow down. This ionizing radiation causes scintillation within the diagnostic, producing light which is fed to a

photomultiplier tube (PMT). The PMT produces a current in response to the light, which is then read by an oscilloscope.

The oscilloscope measures the voltage curve, and records various measurements such as the peak voltage and the voltage integrated over time. For each shot, the oscilloscope is triggered and records the values in the form of a text file. These files then get stored in a selected folder. At the start of the day, a new folder is created manually to contain all the text files written that day. This data is difficult to analyze, as it requires one to go from one file to another in order to compare electron production shot to shot. To combat this problem, a Python code was

written by myself that takes in a day's folder, searches through the text files for the values wanted, then stores them in a single CSV file. This allows one to produce a plot, showing peak voltage which is proportional to the number of electrons produced. This allows for easy confirmation of electron generation when testing various parameters.

The scintillator was useful to detect the presence of electrons, especially in the beginning of the experiment when there were plenty of issues to work out. However, in order to maximize electron production, an additional diagnostic was necessary. The sensitivity to signal which made the scintillator so helpful led to it

Fig 4. Uncalibrated electron energy spectrum from lanex diagnostic.

saturating very easily, as seen in Figure 3.

To see changes in electron production above the saturation limit of the scintillator, a lanex screen was placed in the target chamber before the lead block. Lanex is a scintillating material, so when hit by electrons it emits light which can be imaged by a camera. The images were analyzed using a program called ImageJ. This program allows one to integrate the intensity of each pixel in the image, yielding a value proportional to the electron production. These values can then be paired with the scintillator data, giving a dynamic range for electron detection.

In addition to measuring total charge fluence, the lanex screen can also measure the energy spectrum of the produced electrons. More energetic electrons will be deflected less by the magnet. By measuring the counts across a range of pixels, an uncalibrated spectrum can be found. Figure 4 shows the spectra obtained from two different runs.

Conclusions

The data collected from the scintillator and lanex screen need further analysis to get more valuable conclusions.

The scintillator data could provide some conclusions on the production of electrons from LWFA once the measurements have the associated parameters paired with them. For instance, knowing that changing the laser focus made no difference in electron production, while gas pressure had a dramatic effect, would be valuable for experimenters working on particle acceleration as well as further betatron studies. In addition, integrated counts from the lanex screen can be paired with the scintillator to show consequences that cannot be detected above the saturation limit.

The lanex screen could also yield some valuable measurements if a calibrated energy spectrum is calculated.

This requires one to use the setup geometry to calculate electron energy as a function of position on the screen.

Despite the fact that much more analysis needs to be done, some statements can be made from this data. The scintillator Python code functions correctly, and can be used for further experiments. Additionally, the data collected from the scintillator shows that it functions with sensitivity for minimal electron production. This is valuable for future experimenting, where other diagnostics may fail at detecting electrons because the counts are too low. Regarding the lanex screen, some consistencies in the curvature of the uncalibrated spectra mean that the ImageJ readings were successful at selectively analyzing LWFA electrons and omitting background.

Acknowledgments

My mentor Siegfried Glenzer

My co-mentor Will Shumaker

My co-worker, peer, and friend Florian Condamine

Experimental team:

Felicie Albert

Ben Barbrel

Eric Galtier

Eduardo Granados

Alessandra Ravasio

Kramer Akli and all of Scarlet Laser Facility

SLAC

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