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Scanning transmission ion microscopy computed tomography (STIM-CT) for inertial confinement fusion (ICF) targets

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HIGHLIGHTS

- ICF target quality requires surface finishes on the order of submicron-scale.
- In STIM inner and outer wall profile can be mapped.
- In STIM the thickness and nonconcentricity of shell-wall in ICF targets can be measured.
- STIM-CT is a powerful method for obtaining three-dimensional density maps within ICF targets.
- STIM-CT can obtain internal structure with identifying non-uniformities in the ICF targets.

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ABSTRACT

ICF target quality control in the laser fusion program is vital to ensure that the energy deposition from the lasers results in uniform compression and minimization of Rayleigh–Taylor instabilities, which requires surface finishes on the order of submicron-scale. During target fabrication process the surface finish and the dimensions of the hohlraum need be well controlled. Density variations and nonspherical or nonconcentric shells might be produced. Scanning transmission ion microscopy computed tomography (STIM-CT) is able to reconstruct the three-dimensional quantitative structure of ICF targets a few tens of micrometers in size. Compared to other types of probe techniques, the main advantage of STIM-CT is that quantitative information about mass density and sphericity can be obtained directly and non-destructively, utilizing specific reconstruction codes. We present a case of ICF target (composed of polyvinyl alcohol) characterization by STIM-CT in order to demonstrate the STIM-CT potential impact in assessing target fabrication processes.

1. Introduction

In inertial confinement fusion (ICF), targets for direct-drive experiments consist of a spherical capsule made of glass or plastic that contains the D or DT gas used in these experiments [1]. Target structure as well as the intensity and shape of the driving pulse is vital to ensure that the bombarding laser energy yields high compression of the fuel and ignition [2]. To minimize Rayleigh–Taylor instabilities, current direct drive inertial confinement fusion (ICF) targets require surface finishes. Density variations and nonspherical or nonconcentric shells produced during the fabrication process can cause hydrodynamic instabilities. Non-uniformities of targets are the main source of perturbations which cause a departure from one-dimensional performance [3]. Polyvinyl alcohol (PVA) is one of the materials used in ICF capsules and has higher tensile strength and is less permeable to hydrogen isotopes than polystyrene (PS). However, PVA is easily degraded by beta radiation, which leads to a reduction in nominal retention capability [4]. The surface finish should be appropriate for the current ICF experiments. Using an interfacial polycondensation reaction (IPCR) to produce the membrane leads to an improved surface finish [5,6].

To diagnose a single ICF target capsule, the ideal analysis method would be non-destructive, accurate, sensitive and have the ability to measure the areal density, total concentration and homogeneity. There are a number of methods for diagnosing target capsule. X-ray fluorescence (XRF) can measure elements with $Z \geq 11$ with elaborate procedures to allow precision quantification of dopants in shells; Scanning transmission electron microscopy/energy dispersive X-ray diffraction (STEM/EDXRD) can be used to analysis structure and composition of solid specimen with 5–500 nm thick;

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auger electron spectroscopy (AES) with ion milling is able to characterize the composition of all elemental except H and He. It can similarly characterize the sample in depth. The surface of the shell and the cross section of a fractured wall were observed using a scanning electron microscope (SEM) or an atomic force microscope (AFM) using a knife to broke the shell in order to produce a cross section of the wall [7]. Other techniques, such as mass spectroscopy (MS), thermo gravimetric analysis (TGA), and atomic absorption (AA), are discussed in Ref. [8] as well as in numerous other publications.

Furthermore, there are several conventional methods to describe the density or thickness of materials. The method of X-ray phase contrast imaging or X-ray phase-contrast computed tomography (CT) can provide substantially increased contrast over conventional absorption-based imaging [9] and is suitable for weak-absorption materials and to diminish the total absorption dose [10]. The positron emission tomography (PET) or positron emission tomography computed tomography (PET-CT) is suitable for mapping samples with millimeter-level spatial resolution. By comparison, scanning transmission ion microscopy (STIM) has the potential for producing structural images of sample. STIM relies on measuring the energy loss of a beam of highly focused MeV ions as it passes through a sample. Because the transmitted protons in general maintain a straight path as they pass through sample, then a high quality structural image of a relatively thick specimen can be formed [11]. Combining the modern computed tomography (CT), STIM allows for nondestructive quantitative characterization of targets without slicing sample itself [12–14]. The technique of CT is used to determine the 3D distribution of a physical property in a specimen from a set of projections taken at different orientations [15]. STIM-CT is a powerful non-destructive tool for obtaining three-dimensional density maps and identifying non-uniformities within the targets [16] with a high probing efficiency (nearly 100%) and low ion beam current (∼fA). Features such as thickness variations or shell delamination in ICF targets are distinguished with micron and submicron-scale spatial resolution due to the small beam size [17]. The depth resolution is several tenths nanometers influenced by the stopping power of incident ion, the energy resolution of the STIM detector and the energy straggling. STIM-CT could be explored how accurately we can resolve geometric defects. It also measured a target with density variations caused by latex sphere clusters similar in density and composition to the hydrocarbon matrix. The physical quantity measured in scanning transmission ion micro-tomography (STIM) is the energy loss of the ions. This primary data can then be fed into a STIM-CT 3D reconstruction process [18], assuming that sample is homogeneous in composition. Because of this energy-loss mechanism, we can obtain quantitative total density measurements with the advantage that low atomic number (Z) constituents are not masked by their high Z counterparts.

In STIM, a single projection, which can be used to identify the shape or sphericity of the ICF target, does not allow visualisation of the internal structure of the sample. The internal structure becomes accessible using the tomography technique. The intention of this paper is to describe the system and present the examples of STIM-CT characterization of ICF targets for three-dimensional density, homogeneity, and concentration in order to demonstrate the capabilities of the technique as a means of assessing future ICF target production methods for the first time.

2. Experimental setup and conditions

The experimental setup has been designed especially for 3D-tomography analysis of ICF targets. A schematic diagram of a STIM-CT experiment is shown in Fig. 1. A windowless Si-PIN diode

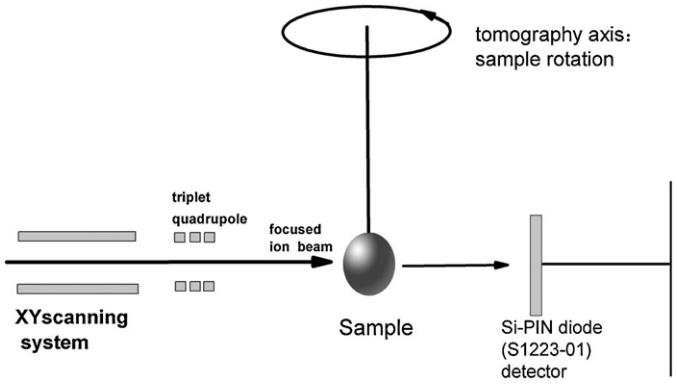

Fig. 1. Schematic diagram of a STIM-CT experiment. For the experiment described in this paper, the spot size of the incident beam at the specimen surface was adjusted to 2 μm. Energies of protons are measured with a Si-PIN dector.

(Hamamatsu 1223-01) with a resolution of 25 keV at full width at half-maximum (FWHM) is placed behind the sample holder (about 6 mm away from the sample) and measures the residual energy of the protons after traversing the sample. The detector suffers from damage during the experiment since the protons are implanted into the crystal. Thus, as soon as the deviation of the measured energy for protons in vacuum decreases, the detector is whirled to expose a fresh region [18]. A sample manipulator with a steel needle is utilized as rotation axis. The manipulator is attached to a PC magnetic rotary drive unit, which is based on an x–y–z target manipulator (x, y: ±12.5 mm, z: 0–50 mm, step: 5 μm). The manipulator can be used to correct the specimen position in case it moves out of the field of view during specimen rotation at the beginning data acquisition [19]. During the experiments the projection angle of the tomography axis is performed by a computer controlled precision step motor. The step motor is capable of rotation in minimum step of 0.05°. The control and data acquisition system of the microprobe facility is running on a PC under MS Windows 2000. The detectors of STIM is connected to OM1000, which convert the analog signals to digital signals. The computer controls the scanning size (range 2 mm × 2 mm) with the Oxford Microbeams Ltd. Data acquisition (OMDAQ) system. The data acquisition and the 3D-scan analysis are fully automated.

A single shell target composed of polyvinyl alcohol (PVA) was prepared for the first experiment. These microspheres were chosen as a model for STIM-CT study due to their regular spherical shape, certified relatively good sphericity, concentricity characteristics and low mass density of 1.19–1.31 g/cm^3. The composition, at least for the main chemical elements, is assumed uniform within all the volume. Although the size of these microspheres does not reach sub-micron level, they are suitable for a first test in STIM-CT. The sample was mounted on top of steel needle using cyanoacrylate adhesive or super glue and then was simply dried in air about 12 h. The sample was aligned along the vertical axis in air and in vacuum.

A 3D-STIM-tomography experiment consists of recording a number of 2D-STIM images of the sample, called projections, under different incident angles from 0–180° (the third dimension) [20]. From these projections the 3D density distribution can be reconstructed. In our experiment, a 3 MeV H^+ beam was used as a probe. The current rate was adjusted to 1000–3000 Hz to avoid any damage of the sample during the analysis. In these conditions, STIM-CT is considered as a non-destructive technique. The transmitted ions are collected in detector, mechanically whirled at 0° on the incoming beam axis during the acquisition [21].

For the analysis the sample was scanned over an area of 750 μm × 750 μm with a total of 128 horizontal slices, obtained