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Reconstruction of Ge spatial distribution in ICF target using PIXE-T

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HIGHLIGHTS

- PIXE-T is proven to be suitable to reconstruct Ge spatial distribution in ICF target.
- One program run in MATLAB is developed to reconstruct elements' spatial distribution.
- The program can compensate loss of X-ray yield in PIXE-T.

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ABSTRACT

Inertial confinement fusion (ICF) target is a microsphere with diameter at millimeter scale and shell thickness at micrometer scale. Ge-doped glow discharge polymer (GDP) is an ideal material for the target. The homogeneity of dopant is vital for uniform compression and minimization of Rayleigh-Taylor (RT) instabilities in ignition. However, the method of quantitative measurement of dopants' spatial distribution is still not mature. Quantitation is not accurate and image resolution is low. Particle induced X-ray emission tomography (PIXE-T) is a suitable technique for measuring trace elements' spatial distribution in small sample at micrometer scale. This paper demonstrates the capabilities of PIXE-T to obtain quantitative spatial distribution of dopant (Germanium) in ICF target for the first time. We also developed a program run in MATLAB to reconstruct Ge spatial distribution 3D image using Filtered Back Projection (FBP) algorithm. When ion beam is transmitted through the target, its energy is attenuated due to collisions. This energy attenuation causes decrease of X-ray emission cross section. For X-ray emitted from target inside, it will be absorbed by target itself before being collected by detector. Both effects cause loss of X-ray counts, especially at the rear of target toward beam. The program can compensate the loss of X-ray counts caused by these two effects, non-linear X-ray production (NLXP) along the path of the beam and X-ray attenuation (XA). This correction is based on a uniform mass density (1.08 g/cm^3) and a uniform major composition (stoichiometric ratio C:H = 5:7 for GDP material) within the sample. Corrections are applied before tomographic reconstruction, producing a more accurate Ge spatial distribution image. After converting X-ray counts in every voxel to Ge concentration using standard reference material (SRM), the image shows quantitative spatial distribution.

1. Introduction

Inertial confinement fusion (ICF) is an approach to fusion that relies on the inertia of the fuel mass to provide confinement. To achieve conditions under which inertial confinement is sufficient for efficient thermonuclear burn, a target (generally a spherical shell) containing thermonuclear fuel is compressed in an implosion process to conditions of high density and temperature [1]. ICF targets rely on either electron conduction (direct drive) or X-ray (indirect drive) for energy transport to ablate the outer layer, creating compression via the rocket effect and eventual ignition. Polymer material is suitable for target because it owns the advantages of low density, which can reduce consumption of radiation energy during the implosion process and RT instability, meanwhile, polymer shell of micro-balloon is easily to be penetrated by soft X-ray aroused by diagnostic elements [2]. Among different polymers, GDP is being used recently in Refs. [3,4]. Target shell is usually named ablator. High-Z doping into the plastic (CH) ablator layer not only can suppress laser imprinting but also can reduce the RT growth rate due to the enhanced radiation preheat at the ablation surface [5].

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Germanium or Silicon is often used as dopant, reported in Refs. [5,6]. The homogeneity of Ge spatial distribution is vital for uniform spherical compression to limit hydrodynamic instabilities.

There are already some techniques that can be used to detect element compositions in ICF target. Energy diffraction spectrum and X-ray photoelectron spectroscopy are used in Ref. [7] to measure the mass fraction of P in Ni-P coating on ICF target surface. X-ray fluorescence is used to measure dopants' planar distribution in China Academy of Engineering Physics (CAEP). But these methods can only measure average element concentration or elements' planar distribution. 3-D confocal micro X-ray fluorescence (CMXRF) is used to measure the spatial compositional and morphological information of target [8]. The depth resolution of CMXRF varies between 100 μm at 1 keV fluorescence energy (Na-K_α) and 30 μm for 17.5 keV (Mo) [9]. Its depth resolution is worse compared with micro ion beam technique. For PIXE-T, its spatial resolution is almost the same with ion beam size, which can reach 1 μm in Ref. [10].

In Fudan University, PIXE has been used to measure elements' planar distribution and composition in samples, covering fields like biology [11], geology [12] and archaeology [13]. It has many advantages, like non-destructive analysis, high sensitivity for trace elements and high resolution of micro-scale. PIXE has already been proven useful to measure Ge planar distribution in ICF target in our laboratory [3]. However, planar measurement can't provide depth profile information. PIXE-T, which combines PIXE with tomography, is one suitable method to measure elements' quantitative spatial distribution. By far, most of PIXE-T focus on biological sample, like *Caenorhabditis elegans* [14,10], flagellates [15], human cancer cells [16] and hair [17]. In order to improve counting statistics for X-ray emission, both high beam intensity of more than 100 pA (for proton) and long collecting time of several hours are needed. However, mass loss and change in morphology are reported in Refs. [10,15,17]. Based on projections taken during PIXE-T and scanning transmission ion microscopy tomography (STIM-T) experiments, the target doesn't have morphological change (like shrink) under several hours' exposure to proton beam. The sensitivity of PIXE-T is the same with PIXE. Theoretically, when using 4 MeV proton beam, the minimum detectable concentration of Ge is 1–2 ppm. The spatial resolution of PIXE-T can be seen as same as ion beam size, which can reach ~10 μm for PIXE-T experiment in our lab. PIXE-T is suitable to analysis ICF target.

In the case of thick samples in PIXE-T, like ICF target, quantitative reconstruction requires a correction. The correction needs to take into account the variation in ionization cross section due to ion beam energy loss (on the way to the emission point) and the attenuation of the emitted X-rays from the emission point to the detector [18]. In short, two effects are non-linear X-ray production (NLXP) and X-ray attenuation (XA). Because of NLXP along the path of beam and XA, detected characteristic X-ray counts is lower than actual situation [10,17]. Without correction, after converting X-ray counts to element concentration, concentration will also be lower than actual situation, especially at the rear of target toward incident beam. Mass density can be used to calculate stopping power of target material and X-ray mass attenuation coefficients. With the help of mass density, loss of X-ray counts can be corrected, obtaining a more accurate image [19]. STIM-T which measures residual energy of transmitted protons can obtain mass density spatial distribution image [20,21]. It is usually used to correct X-ray yield in PIXE-T [19,22,23]. Several quantitative reconstruction techniques have been developed, like JPIXE-T [10,24], Tomorebuild [14,23,25] and DISRA [26]. However, some parameters in reconstruction algorithm are not easy to modify. MATLAB, as a commercial software, has incorporated the function "iradon", which uses the FBP algorithm to perform inverse Radon transform. Several ready-made filters are easy to be called and modified. We developed a program run in MATLAB to complement the correction, which considers both effects of NLXP and XA. This program is user-friendly to modify parameters.

2. Experiment

A schematic diagram of our experimental apparatus is shown in Fig. 1. Proton beam is provided by a NEC 9SDH-2 Tandem accelerator at Institute of Modern Physics in Fudan University. The scanning system, triplet quadrupole lens and data acquisition software OMDAQ are purchased from Oxford Microbeams Ltd. A detailed description can be found in Ref. [27]. A Si(Li) detector (Sirius80, Gresham Ltd.) with 80 mm^2 active area and energy resolution of 150 eV at 5.9 keV is installed at 135° with respect to beam direction to collect proton induced X-rays. Kapton film of 24 μm (3 stacked layers of 8 μm) is added in front of Si(Li) detector to attenuate low energy X-ray and to stop backscattered particles. A CCD camera is installed at 135° with respect to beam direction on the other side to observe sample movement and the position of beam. A windowless Si-PIN diode detector (1223-01, Hamamatsu Ltd.) is installed right behind target. It is used to measure residual energy of transmitted particles. Sample manipulator can be moved manually in XYZ direction (X, Z: ±12.5 mm, Y: 0–50 mm, step: 5 μm). Meanwhile it rotates 360° clockwise (see from top) driven by a self-designed magnetic rotary drive unit with a minimum step of 0.05°. The step motor is controlled by computer [28]. In this paper, 4 MeV proton beam is focused to 5 μm × 10 μm. 31 projections were taken at an interval of 6° over a range of 180°. Collecting time is set to be 30 min/projection. For every projection, scan size is 500 μm × 500 μm with 128 pixels × 128 pixels, producing pixel size of ~3.9 μm in both width and height. As the PIXE beam spot size was bigger than the pixel size, the pixels overlapped. Therefore surrounding pixels may contribute to the X-ray count at a pixel. This is a particular problem at sharp boundaries where characteristic X-rays may be detected even though the element of interest is not present [10].

An ICF target made of Ge doped GDP material is used. Specific fabrication process has been published in Ref. [3]. The polymer's stoichiometric ratio is C:H = 5:7 measured by combustion method in CAEP. Target's diameter is 392 μm and shell thickness is 25 μm. Mass fraction of dopant Ge is ~5%. Ge is supposed to be doped homogeneously which need further confirmation in following reconstruction. Both morphological parameters and doping quantity are measured by contact radiography in CAEP. The measurement process is similar with [29,30]. Target's mass density is 1.08 g/cm^3. The measurement is simply using mass/volume.

The target is fixed downwards at the bottom tip of an iron needle, which is also the rotation axis. Sample fixing is a difficult task in tomography. Because reconstruction algorithm such as FBP [31] requires to probe the sample over at least 180°. For this, the sample needs to be mounted as freestanding, attached to the tip of the rotation axis [18]. In our previous experiment, we used fluid glue to stick target at the tip of rotation axis. But because of tensile force of fluid, the glue will easily spread and cover a large area of target, bringing unavoidable contamination. The glue contains Chlorine which is not contained in target. This contamination has been proven by unexpected distribution of Chlorine on the target, especially near the fixing position. Recently, we improved target fixing method by using carbon conductive tape used in scanning electron microscope. Solid tape avoids the undesired spread of fluid glue, only contacting target in a small area. The fixing process also becomes easier. Previously, we have to wait for over an hour until the fluid glue solidifies. Now we only need to wrap some tapes on the rotation axis and touch one target gently. Besides, element carbon can't be detected by PIXE. There is no impurity influence in PIXE