Study on the static detection of ICF target based on muonic X-ray sphere encoded imaging

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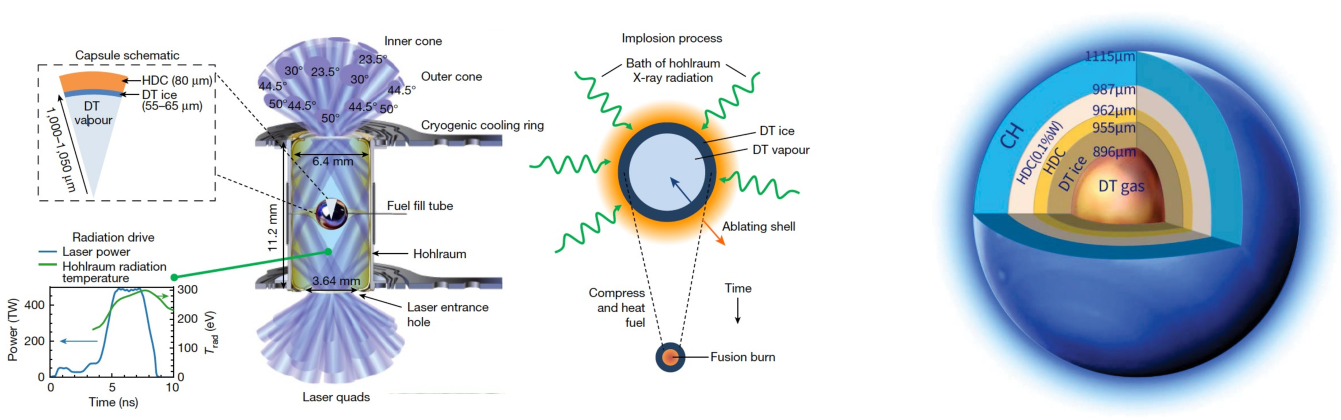
Introduction

In December 2022, the U.S. Department of Energy announced a major breakthrough at the National Ignition Facility, achieving fusion ignition, signifying that the energy from the fusion exceeded the initiating laser energy. This has rekindled interest in Inertial Confinement Fusion (ICF) due to its potential scientific and technological benefits. ICF targets, consisting of a deuterium-tritium core and multiple material layers including high-density carbon, require precise diagnostic methods to assess internal structures and elemental distributions. However, traditional methods like X-ray imaging are inadequate for detailed mapping at the required micron level. Figures 1a and 1b illustrate the fusion process and the multi-shell structure of an ICF capsule, emphasizing the need for accurate defect mapping and internal structure imaging with micron precision.



(a) (b)

Fig1.ICF target：(a) NIF schematic[1] , (b) Multi-shell ICF target[2]

Muon-Induced X-ray Emission (MIXE) was discovered by Zhang Wenyu in 1947[3]. Advances in MIXE research, including technologies by Hillier, Katsurakawa, and Pan[4], have improved imaging but still do not meet the micron resolution needed for ICF target inspection.

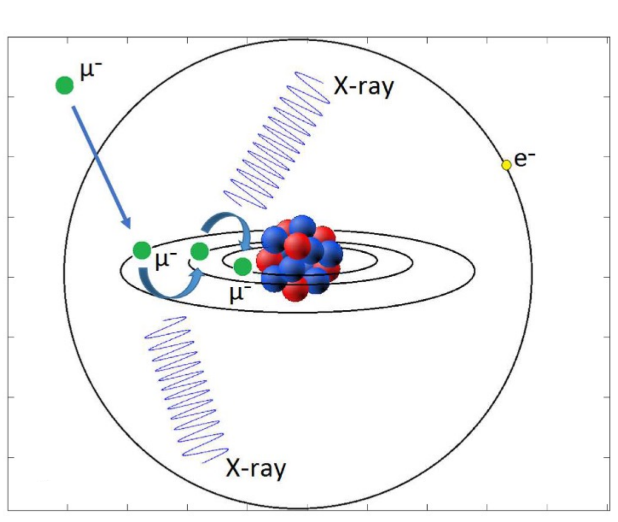


Fig2. Muon-Induced X-ray Emission process[5]

This work integrates MIXE with spherical coded imaging technology to enhance non-destructive, high-resolution imaging capabilities for deep internal and elemental analysis of ICF targets.

According to reference[6,7], utilizing a spherical coded system enhances the spatial resolution of X-ray source imaging to the micron level.

$$h = \sqrt{\left(\frac{e}{M}\right)^2 + p\lambda + L^2 + (\Delta d)^2}$$

This report employs the Geant4 simulation framework to model the generation of characteristic X-rays by muon irradiation onto ICF target capulse. The X-rays produced are coded through a lead sphere, captured on a flat panel detector as encoded images.

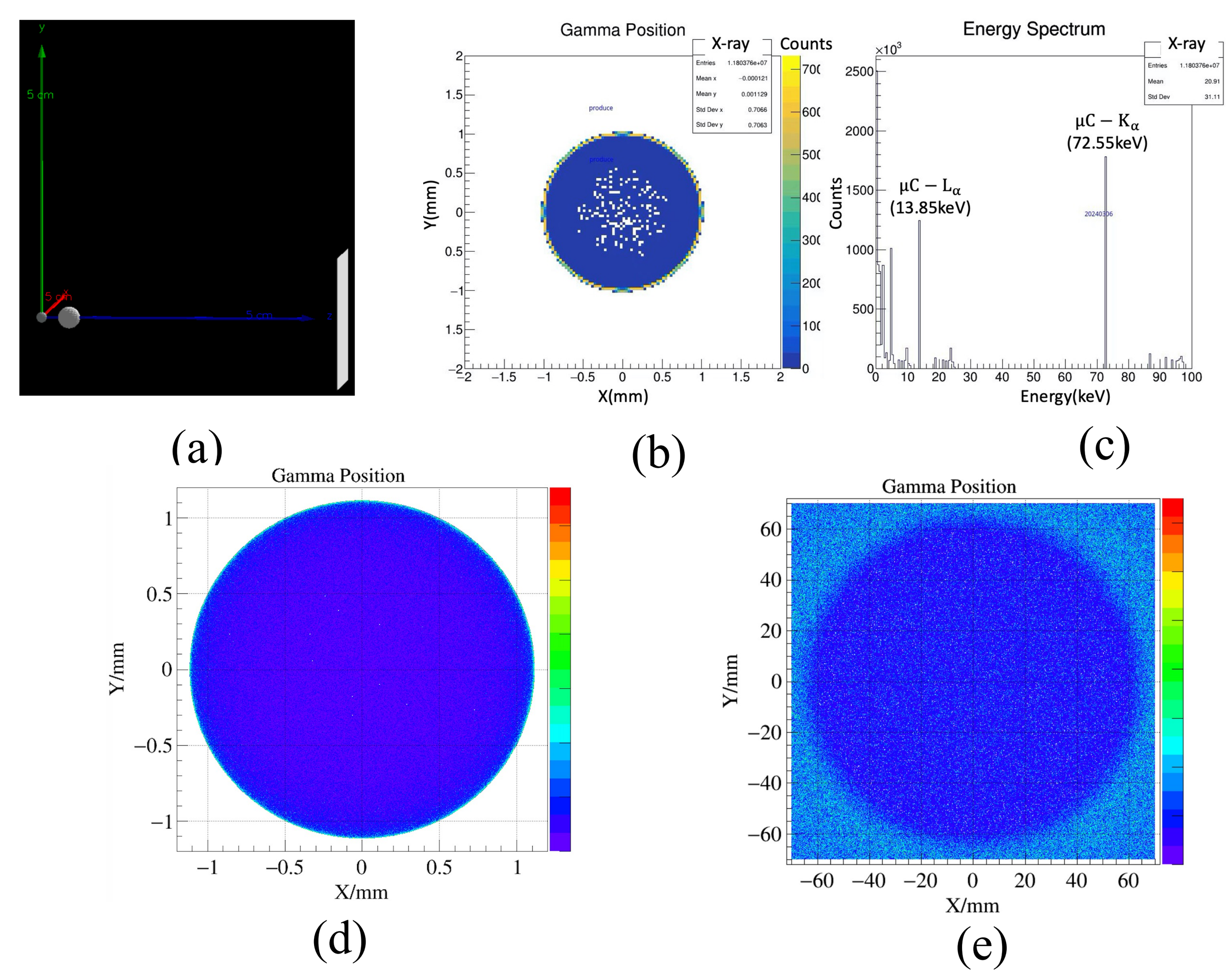


Fig3. Geant4 simulation results of X-ray from MIXE of ICF target encoded by a sphere

Fig3a: Geometric schematic showing the arrangement with the smallest sphere on the left representing the HDC shell of the ICF target, followed by a lead sphere, and a flat panel detector on the far right. Fig3b: Two-dimensional distribution of the generated X-rays, matching the projection of a spherical shell. Fig3c: Energy spectrum of the X-rays, displaying a distinct carbon peak. Fig3d: Two-dimensional distribution of the X-rays exiting the target pellet. Fig3e: Distribution of the X-rays reaching the detector after encoding through the lead sphere. The coded image Fig3e is subsequently decoded and reconstructed using Wiener filtering and the Richardson-Lucy (R-L) algorithm. More results and details can be found at arxiv.

主要参考文献

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