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ICF Neutron Detection Techniques Based on Doped ZnO Crystal

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Abstract**—**Ultrafast doped zinc oxide crystal promised us a good opportunity to build new instruments for ICF fusion neutron measurement. Two pulsed neutron detectors based on ZnO crystal wafer have been conceptually designed, the superfast ZnO timing detector and the scintillation recoil proton neutron detection system. The structure of these detectors was presented, and some characters were studied as well. The new detectors could be much faster than existing systems, and would be more competent for ICF neutron diagnostics.

Keywords**—**ICF fusion neutron detection, proton recoil telescope, superfast timing, ZnO crystal

I. INTRODUCTION

KNOWN as an ultrafast scintillation material, doped zinc oxide (ZnO) has drawn great interest in the past decade, focusing on growing high quality crystals and optimizing its luminescence performance [1]-[4]. Those fast doped ZnO crystals typically have a rise time below 100 ps and decay time below 1 ns, which is deeply related to crystallization quality and dopants added. Most of the researches were based on ZnO doped with In or Ga. Some other dopants were studied as well, including Al, Cu, Zn, Fe etc. It is reported that ZnO doped with Fe has a fluorescence rise time only 2.1 ps and decay time around 70 ps to X-ray free electron laser excitation [5]. This excellent performance is much faster than traditional ultrafast plastic scintillator, like BC422Q which could achieve a rise time around 20 ps [6] at the cost of light yield. Some doped ZnO crystal products are commercially available nowadays, such as the ZnO:In and ZnO:Ga crystals from the Cerment Inc [7], however, the size is limited. Although light yield of these products is relatively low, below 1000 photons/MeV according to our research, which limits the application for individual particle scintillation counting or radiation imaging, it can work properly for pulsed radiation measurement [8]. Doped ZnO crystal promised us an opportunity to build new diagnostic instruments for the measurement of pulsed fusion neutron generated from inertial confinement fusion (ICF) devices. There are many ICF devices working or under construction around the world, like the most powerful National Ignition Facility [9] and the Laser Megajoule Facility [10], as well as the series of Shenguang Laser Facility [11] in China. Fusion neutron diagnostics characterize fusion performance, and help to provide the understanding needed to develop high yield sources. Many kinds of neutron detection systems were configured for measuring fusion neutron intensity, time property, energy spectrum, and spatial distribution [12, 13]. Since the ICF process lasts very short, only several tens of picoseconds for NIF [14], and the yield of neutron varies greatly from shot to shot, neutron detectors with ultrafast time response, as well as high sensitivity, wide dynamic range, high discrimination and accuracy are required. To fulfill the specific requirements of ICF neutron detection, two neutron detectors based on doped ZnO crystal wafer were conceptually designed, and the new detectors could have better performance than existing systems.

II. SUPERFAST ZNO TIMING DETECTOR

ZnO can be used for 14 MeV neutron detection directly, through (n,p) and (n,α) reactions with zinc and oxygen. For example, ZnO:Ga powder once been designed for selective fast neutron detection on Tokamak devices [15]. Current scintillation detectors being used for ICF Bang time and nTOF measurements are mostly made of BC422Q coupled with micro-channel plate (MCP) photo multiplier tubes (PMTs) [6, 16]. To optimize the timing performance, thin scintillation wafer is required to minimize temporal spread. Similarly, ZnO crystal applied for ICF fusion neutron timing detection should not be thicker than several millimeters. Consequently, the detection efficiency of this wafer to 14 MeV neutrons becomes very low, below 1% for 1 mm thick scintillator. Furthermore, the scintillation efficiency of both the BC422Q and doped ZnO crystal is very small, which caused the overall sensitivity of this detector extremely low, even lower than the direct response of the PMT to 14 MeV neutrons. It is necessary to keep the PMT away from the neutron beam, and be shielded carefully.

Therefore, the double mirror reflection collection optical structure was designed, as shown in Fig.1. With two abaxial concave mirrors, luminescence from the ZnO wafer was collected and guided to the PMT, which was about half a meter aside of the neutron beam path. The mirror profile was designed with the Zemax optical design software, and the optical path was optimized to minimize the temporal spread and maximize the light collection efficiency. The light collection efficiency is over 10% and the spread of time can be kept below tens of picoseconds, which depends on the area of the ZnO wafer and the diameter of the mirror. By the way, optical lenses were inappropriate because most of the lens materials luminescence under irradiation, and this luminescence could induce additional interferences to this low sensitivity system. A prototype detector was constructed, where the crystal employed was ZnO:In with a diameter of ϕ25.4 mm and a thickness of 0.3 mm. The diameter of the mirrors was ϕ100 mm. The PMT was

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R3809U-50, a two-stage MCP PMT from Hamamatsu with 11 mm diameter photocathode, 150 ps rise time, and a gain around 10^5. The time response of the prototype detector and its response to 14 MeV pulsed neutron were tested on a femtosecond laser source and a dense plasma focus (DPF) pulsed neutron source, respectively.

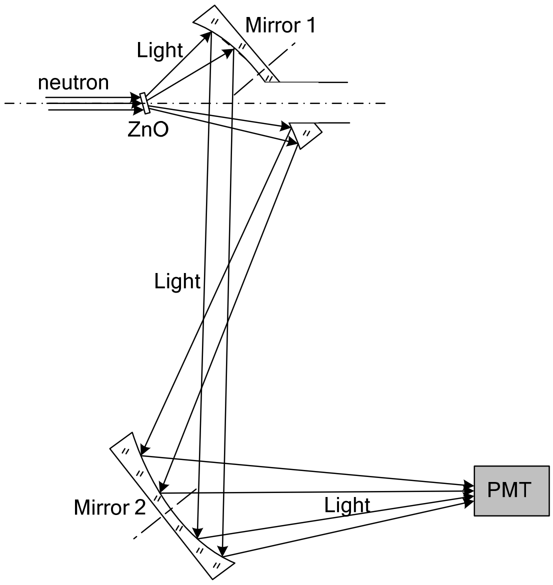

Fig. 1 Double mirror reflection collection optical structure

The time response of the detector is shown in Fig.2. The ZnO:In wafer was excited by wavelength 266 nm light, frequency tripled from the femtosecond 800 nm laser. And the signal from the PMT was recorded by a 4 GHz digital oscilloscope. As the ZnO native luminescence consists of two components, the fast component around 380 nm generated from the exciton annihilation, and the slow component yellow and/or green related to defect states [17], a short-wave pass optical filter with cut-off wavelength around 400 nm was set in front of the PMT to eliminate the slow component. The measured waveform has a 163 ps rise time, which is close to the intrinsic time response of the PMT.

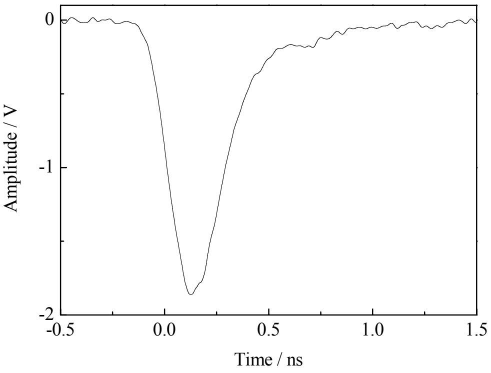

Fig. 2 Time response of the prototype detector to femtosecond laser irradiation (wavelength 266 nm)

The response of the detector to 14 MeV pulsed neutron is shown in Fig.3. The dual-peak waveform correctly represents the character of the DPF neutron generator, type ING-103 from the All Russian Research Institute of Automatics. Bremsstrahlung X-ray pulse generated simultaneously with the fusion neutron pulse, with FWHM time around 20 ns, and separated after transporting a certain distance due to different velocities. The first peak stands for X-rays, and the second peak is for DT fusion neutron. The PMT was shielded properly during the experiment. The direct response of the MCP PMT to 14 MeV pulsed neutron irradiation is shown as well.

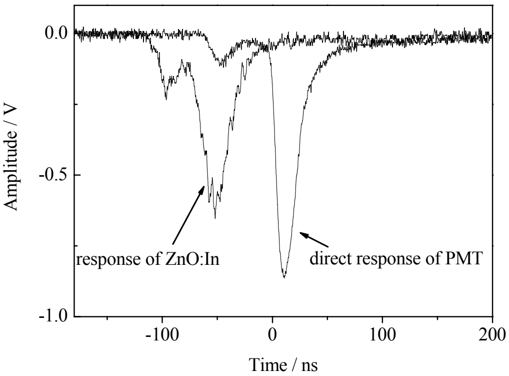

Fig. 3 The response of the detector and the direct response of the MCP PMT to 14 MeV pulsed neutron irradiation

According to our primary experimental results, doped ZnO crystal can work properly for 14 MeV pulsed neutron measurement. The time response of the prototype detector is limited by the PMT and the crystal. However, the time response could be increased by employing ultrafast photon detectors or streak camera. If the ultrafast doped ZnO crystals like ZnO:Fe are used, the detector could achieve a picoseconds time response.

III. SCINTILLATION RECOIL PROTON NEUTRON DETECTION SYSTEM

The proton recoil telescope is a common technique for fast neutron detection. It typically contains a polythene membrane as the recoil proton radiator, and a detector to capture the recoil protons at specific angle with respect to the neutron direction. PROTEX is a kind of recoil proton neutron detector designed for NIF 14 MeV neutron yield measurement [18], and its novel coaxial design greatly increased the detection efficiency of this kind of systems. However, the time response is relatively slow, for large area Si-PIN detector was employed to increase the recoil proton collection efficiency. Si-PIN with diameter of ϕ20 mm has a long tail over 10 ns, and even slower for larger diameter. Different component from the fusion source and scatterings would pile up, and affects the measuring result. Moreover, the adjustability of sensitivity to semiconductor detector is limited.

An optional way to overcome this deficiency is to substitute the semiconductor detector with a scintillation detector. The notable virtue of a scintillation detector is the high sensitivity and the adjustability by changing PMTs with different gains conveniently. However, common fast organic scintillator, which is rich of hydrogen and widely used for fast neutron detection, is incompetent here, because low neutron sensitivity is required to avoid scattering neutron interference. And traditional inorganic scintillators are too slow to be used. Doped ZnO crystals provide us a good choice to build recoil proton neutron detection system based on scintillation techniques, where thin film ZnO crystal would be competent. The schematic diagram of the SRPNDS is shown in Fig.4. The polythene membrane is in the center of the chamber, and a ZnO:In wafer was arranged at the branch facing the target outside the vacuum chamber. The thickness of the ZnO wafer should be thick enough to keep protons from reaching the PMT. By coupling to an ultrafast PMT, the time response of this SRPNDS could achieve to sub-nanosecond. A pair of magnet is arranged on the recoil proton path to deflect secondary electrons generated from the target. Though the amount of secondary electrons may be small, the detection efficiency of a scintillator to electron is 100%. This design is quite important to those pulsed neutron fields mixed with intense X-rays or gamma rays.

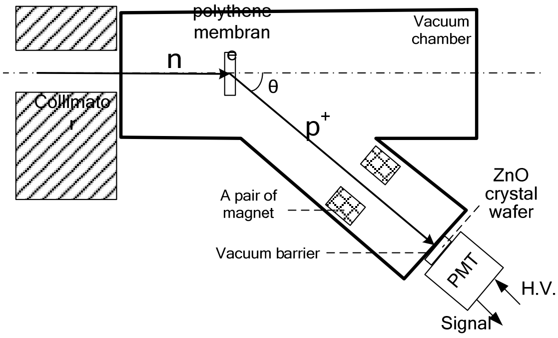

Fig. 4 Schematic diagram of the scintillation recoil proton neutron detection system

According to the working process of the SRPNDS, the average output charge per neutron irradiation (sensitivity) can be expressed as:

$$S = N_{\mathrm{H}} \cdot s \cdot \Delta x \cdot \overline{\sigma}_{\mathrm{n,p}} \cdot \Delta\Omega \cdot ph(E_{\mathrm{p}}) \cdot c \cdot \eta \cdot G \cdot 1.6\times10^{-19} \quad (1)$$

where N_{H} is the density of hydrogen atoms in the polyethylene, s and Δx are the area and the thickness of the polyethylene respectively, $\sigma_{\mathrm{n,p}}$ is the average n, p scattering cross section, $\Delta\Omega$ is the solid angle subtended by the ZnO wafer. $ph(E_{\mathrm{p}})$ stands for light yield from the ZnO wafer irradiated by proton with energy E_{p}. c is the total light collection efficiency, η and G are the quantum efficiency and the gain of the PMT respectively. The sensitivity is in the unit of C/n. The performance of this system could be optimized by adjusting the dimension of the membranes and the collection angle θ, which depends on the requirement of practical use.

Obviously, the response of ZnO:In to proton is key to this SRPNDS. Unlike Si-PIN, the response of a scintillator typically nonlinearly depends on the incident proton energy. So the light yield of the ZnO crystal as a function of proton energy was measured on the accelerator, the result is shown in Fig.5. Although the response of the SRPNDS could be calculated through Monte Carlo simulation, like Geant4 [19], the exact sensitivity should be calibrated experimentally. Relevant research is still undergoing.

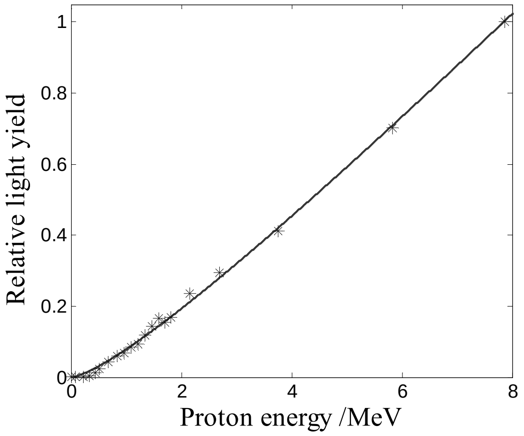

Fig. 5 Relative light yield of ZnO:In crystal to proton

IV. CONCLUSION

Two current mode detectors built with ZnO crystal wafer have been designed, the superfast ZnO timing detector and the scintillation recoil proton neutron detection system. The structure of these detectors was presented, and some characters were studied as well. Since doped ZnO crystal can achieve a picoseconds time response, the ZnO timing detector could be much faster than BC422Q. And the scintillation recoil proton neutron detection system could easily achieve a sub-nanosecond time response. The new detectors would be more competent for ICF neutron diagnostics.

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