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# ICF Burn-History Measurements Using 17-MeV Fusion Gamma Rays



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# ICF Burn-History Measurements Using 17-MeV Fusion Gamma Rays

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**Abstract.** Fusion reaction rate for inertial-confinement fusion (ICF) experiments at the Nova Laser Facility is measured with 30-ps resolution using a high-speed neutron detector. We are investigating a measurement technique based on the 16.7-MeV gamma rays that are released in deuterium-tritium fusion. Our concept is to convert gamma-ray energy into a fast burst of Cerenkov light that can be recorded with a high-speed optical detector. We have detected fusion gamma rays in preliminary experiments conducted at Nova where we used a tungsten/aerogel converter to generate Cerenkov light and an optical streak camera to record the signal.

## INTRODUCTION

The fusion reaction-rate (or burn history) for an inertial-confinement fusion (ICF) target is a valuable piece of information for researchers studying laser-target interactions. It provides a sensitive measure of their ability to accurately model the interaction process. The centroid of the burn history, which is often referred to as the "bang time," depends on the coupling between the incident laser energy and the target capsule, and on the hydrodynamics of the capsule implosion. The details of the burn history, which are often characterized by a burn width, are related to plasma conditions at the time of peak target compression.

At the Nova Laser Facility, we use fusion neutrons from the $D(d,n)^3He$ and $T(d,n)^4He$ reactions to directly measure the thermonuclear burn rate for ICF targets (1). Temporal resolutions of 30 ps are achieved for deuterium-tritium (DT) neutron yields as low as $5 \times 10^8$. Since fusion neutrons are nearly monoenergetic and most of them escape from a small (< 200 μm diam) emission region (2) without collision, they preserve burn history information as they travel radially outward towards a fast detector some distance away.

There are, however, two fundamental limits to the temporal resolution that can be achieved by direct neutron detection. Doppler broadening of the neutron energy spectra causes a spread in the arrival times of the neutrons at a detector, and detector thickness produces a time spread caused by detection point uncertainty. For 14-

MeV DT neutrons, the time spread caused by the thermal motion of the plasma ions is given by $\Delta t = 122\sqrt{T_i} \times d$, where the time spread $\Delta t$ is in ps, the plasma ion temperature $T_i$ is in keV, and the target-to-detector distance $d$ is in meters. Detection point uncertainty for DT neutrons is nearly 20 ps per mm. At Nova we typically make reaction rate measurements with a 1-mm thick detector placed between 2 and 20 cm from a target.

At the future National Ignition Facility (NIF), it is unlikely that reaction-rate measurements with 30-ps resolution can be made directly with fusion neutrons. At this megajoule laser facility we expect an "exclusion zone" to exist in the center of the target chamber. Its radius will be determined by experiment energy and will probably range from 50 cm to 5 meters. To achieve 30-ps resolution, neutron based measurements at NIF will require either a small neutron-to-radiation (gamma ray or light) converter close to the target or a neutron energy selection mechanism.

We are studying the possible use of fusion gamma rays as an alternative to fusion neutrons for making burn history measurements (3). A gamma-ray based measurement is attractive because gamma rays are virtually unaffected by the plasma temperature, have a large interaction cross section in many materials, and produce no time dispersion traveling to a distant detector. The $T(d,\gamma)^5He$ reaction produces gamma rays with energies up to 16.7 MeV. The major disadvantage of this reaction is its low branching ratio of $5 \times 10^{-5}$. In this paper we describe the first observation of fusion gamma rays in an ICF experiment and discuss their possible use for future burn history measurements.

## GAMMA-RAY DETECTOR CONCEPT

Figure 1 shows the basic concept for a gamma-ray based ICF burn history measurement. A target filled with a deuterium-tritium fuel mixture is heated and compressed with intense laser or x-ray radiation. The burning fuel isotropically emits fusion neutrons and gamma rays which travel radially outward from the compressed target core. Some of the gamma rays interact with a two-stage converter to produce Cerenkov light. In the first converter stage, gamma rays produce forward directed, relativistic electrons and positrons by Compton scattering and pair production interactions. The charged particles move into the second converter stage where they produce Cerenkov light. An optical system collects the Cerenkov light and relays it to a fast optical detector such as a high-speed streak camera for recording.

The converter offers the designer a number of options. Final detector design will focus on providing an instrument with good time resolution ($\Delta t < 30$ ps) and sensitivity. The choice of low-Z or high-Z material for the first-stage gamma-ray converter determines whether the primary interaction is Compton scattering or pair production. For 16.7 MeV gamma rays, the interaction cross-section for high-Z

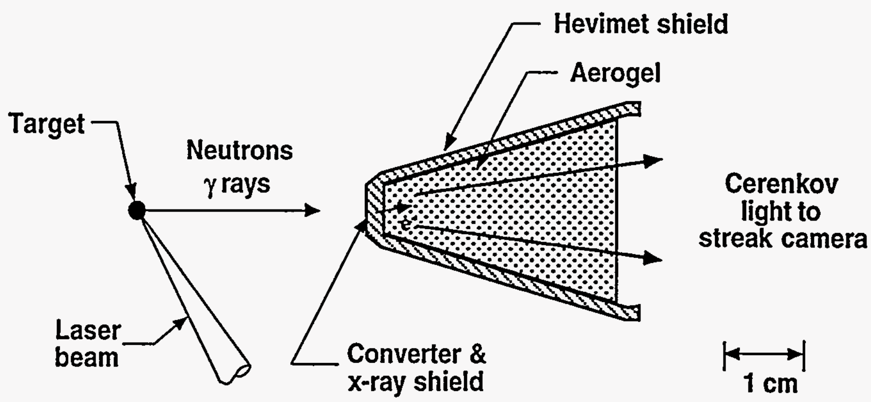


**Figure 1.** Hevimet nose cone acts as a γ ray to charged particle converter as well as a radiation and light shield.

materials is approximately 100 times greater than it is for low-Z materials. The range of the resulting electrons and positrons, however, is much greater in low-Z materials. We estimate that about 15% of the 16.7 MeV gamma rays incident on a high-Z converter that is several millimeters thick produce electron-positron pairs that enter an adjacent Cerenkov converter.

The second converter stage determines the characteristics of the Cerenkov light. The threshold energy for production of Cerenkov radiation, the cone angle for its emission, and the number of photons emitted per centimeter of track length depend on the index of refraction $n$ of the converter material (4). Cerenkov light is produced in a material only when the speed of a charged particle exceeds that of light in that media. Thus, Cerenkov light is produced only when $\beta$ the velocity of a particle relative to that of light in a vacuum and the index of refraction are such that $n\beta > 1$. Cerenkov radiation is emitted into a cone whose half angle $\theta$ relative to the direction of the charged particle motion is given by $\cos\theta = (1/n\beta)$. The photon production rate into the visible spectrum (400 - 700 nm) is given by

$$\frac{dN}{dx} = 490\,(1 - \frac{1}{n^2\beta^2})\ \text{photons/cm.}$$

Detector geometry can be selected to enhance collection of the Cerenkov light (5).

## FUSION GAMMA RAYS OBSERVED

We recently conducted a set of direct-drive target experiments at the Nova Laser Facility to access our ability to detect fusion gamma rays. Yields from 1-mm diam deuterium-tritium filled glass ball targets irradiated with 1-ns square pulses ranged from $10^{12}$ to $2 \times 10^{13}$ DT neutrons. For these experiments, we adapted equipment

normally used for our neutron burn history measurements (1). The standard Hevimet (90% tungsten) nose cone (Fig. 1) acted as the first converter stage in which gamma rays interact primarily by pair production to produce electron-positron pairs. A 0.241 $g/cm^3$ silica aerogel filled the interior of the nose cone replacing the standard 1-mm thick fast plastic scintillator. The aerogel acted as the second converter stage, converting relativistic particle energy into Cerenkov light. With an index of refraction of 1.06, the threshold energy for an electron to produce Cerenkov light in the aerogel is 1.03 MeV and the maximum cone angle for the emitted radiation is 19°. We estimate photon production at the rate of 53 photons per centimeter of track length. An f/2 optical telescope relayed light from the aerogel to a streak camera. System temporal response is better than 15 ps (FWHM). No modifications were made to the equipment to optimize Cerenkov light collection. Indeed, the telescope optics were designed to pass wavelengths between 350 and 450 nm.

Figure 2 shows streak camera signals recorded for target-to-aerogel distances of 2, 3, and 4 cm. Each signal has a large 550 ps wide pulse produced by 14-MeV target neutrons interacting with the silica aerogel. The burn duration for this type target measured in similar experiments is nominally 200 ps FWHM. The 550 ps corresponds to the neutron transit time across the 3.4 cm thick piece of aerogel. In Fig. 2 the neutron-induced signals are normalized, temporally aligned, and overlaid. This allows us to easily observe a small pulse at the foot of the neutron peak. Its time relative to the neutron pulse changes with target-to-aerogel distance in a manner consistent with fusion gamma rays. A 1 cm increase in target-to-aerogel distance produces a 162 ps increase in time between gamma ray and neutron induced signals.

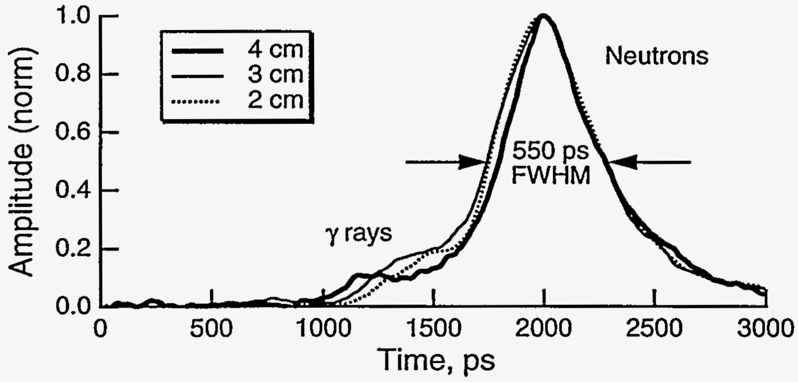


**Figure 2.** Aerogel signal intensity versus time for several target-to-aerogel distances. Neutron-induced signals are normalized, temporally aligned and overlaid. Presented in this fashion, change in gamma-gay signal timing relative to the neutron signal is easily observed. Time base is relative to incident laser power for 4 cm gamma ray data.

The streak camera simultaneously records a fiducial signal along with the aerogel signal. This allows us to determine the time of a gamma ray signal relative to the laser power incident on a target. The time of the gamma ray signal corresponds to the neutron emission time that we measure with a separate bang time detector (6). For these targets, the nominal neutron emission time is at 1 ns.

An additional experiment was performed with an aluminum nose cone replacing the Hevimet nose cone. In this configuration, the pair production cross section for 16.7-MeV gamma rays is reduced by a factor of 25 and the primary interaction mechanism changes to Compton scattering. The results (see Fig. 3) are consistent with the small peak being caused by pair production in the high-Z nose cone. The gamma ray signal observed with the Hevimet nose cone is not observed with the aerogel inside the aluminum nose cone. Also of note, with the substantially reduced shielding of the aluminum nose cone, there is no significant x-ray signal observed between the start of target irradiation and bang time.

## DISCUSSION

These experiments demonstrate our ability to detect fusion gamma rays emitted by the $T(d,\gamma)^5He$ reaction for Nova targets yielding $10^{12}$ to $10^{13}$ neutrons. Several pieces of experimental evidence are consistent with this conclusion. First the change in time-of-flight separation between gamma ray and neutron pulses is consistent with the target-to-aerogel distances used. Second, the gamma ray signals occur at the bang time of the target as determined with a separate neutron detector. Finally, the gamma ray signal is strongly dependent on the change of first stage converter material from tungsten to aluminum in a manner consistent with pair production.

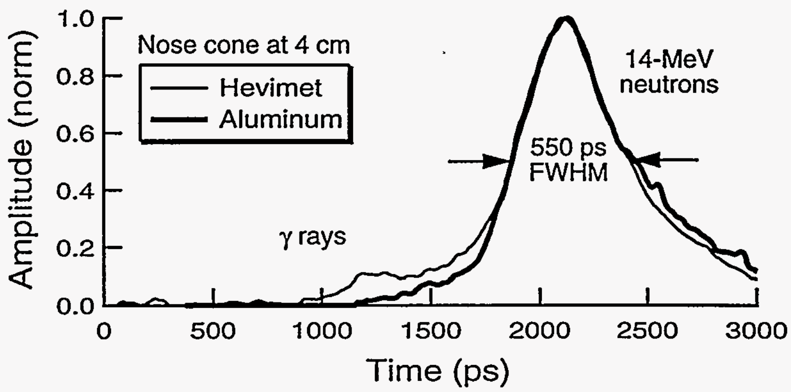


**Figure 3.** Aerogel signal intensity versus time for Hevimet and aluminum nose cones. Gamma-ray signal depends on high-Z converter material.

Additionally, the reduced shielding of the aluminum nose cone resulted in no noticeable increase in detected x rays, suggesting that we are indeed seeing fusion gamma rays and not target x rays.

Future effort will be directed at developing a sensitive burn history detector based on fusion gamma rays. To retain temporal response < 30 ps, we imagine the detector will remain a streak camera. There are several areas where significant improvements to sensitivity can be made. Improved optical transmission of the second converter stage will certainly enhance the signal. Our aerogel sample has relatively poor (< 20% through 7 mm) transmission for wavelengths < 500 nm. Similarly, optical transmission of the relay optics between the converter and streak camera can be greatly improved. Current optics were designed to transmit wavelengths between 350 and 450 nm. The streak camera has an S20 photocathode with a UV-grade sapphire window and good sensitivity for wavelengths between 250 and 700 nm. Additional gains in sensitivity can also surely be made with careful selection of converter materials and converter geometry.

## ACKNOWLEDGMENTS

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