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GEANT4 simulations of Cherenkov reaction history diagnostics[a)]

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This paper compares the results from a GEANT4 simulation of the gas Cherenkov detector 1 (GCD1) with previous simulations and experimental data from the Omega laser facility. The GCD1 collects gammas emitted during a deuterium-tritium capsule implosion and converts them, through several processes, to Cherenkov light. Photon signals are recorded using subnanosecond photomultiplier tubes, producing burn reaction histories. The GEANT4 GCD1 simulation is first benchmarked against ACCEPT, an integrated tiger series code, with good agreement. The simulation is subsequently compared with data from the Omega laser facility, where experiments have been performed to measure the effects of *Hohlraum* materials on reaction history signals, in preparation for experiments at the National Ignition Facility.
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I. INTRODUCTION

Gas Cherenkov detectors have been designed for the detection of deuterium-tritium (DT) fusion γ rays at Inertial Confinement Fusion (ICF) facilities.[1] Using γ photons to measure the reaction history (RH) can be advantageous compared with neutron measurements due to source temperature induced temporal spreading of neutrons over large distances.[2] The branching ratio for the 16.72 MeV γ channel,[3] however, is less frequent $(2\pm 1)\times 10^{-5}$. Measuring 16.72 MeV γ photons directly is difficult; Cherenkov detectors solve this by converting the γ to an electron using a low-Z metal and channeling the electron through a high-pressure gas with suitable refractive index for Cherenkov emission. Light is subsequently focused onto a photomultiplier tube (PMT). Gases and pressures used are CO_2 and SF_6 and 10–200 psi, respectively. Index scales with SF_6 pressure, as shown in Fig. 1.[4] To emit Cherenkov light, an electron must exceed the local speed of light $v_e = cn^{-1}$; combining this with the full backscatter condition, $\varphi = 180°$, for the Compton scattering process,[5] the lowest energy γ is therefore

$$E_\gamma = \left[\frac{1}{(1-1/n^2)^{1/2}} - \frac{1}{2}\right] m_e c^2,$$

where E_γ is the required incident γ energy, n is the refractive index, m_e is the electron rest mass, and c is the vacuum speed of light. Consequently, in a dispersive medium, there are a continuous range of incident γ thresholds with the lowest corresponding to the shortest Cherenkov emission wavelength, defined by the transmission minimum of the PMT input window. Throughout this paper, the threshold will be described as such.

II. GAS CERENKOV DETECTOR 1

The GCD1, shown in Fig. 2, has routinely recorded direct drive, symmetric RHs at the Omega laser facility for almost a decade.[6] The converter region is composed of Al, Be, and Pb; Al and Be are efficient γ-electron conversion metals, and Pb reduces the laser-plasma x rays from interacting with the gas.[7] Following the converter is a gas cell, a tungsten block to scatter unconverted fusion gammas, Cassegrainian optics, and a PMT.

III. SIMULATIONS

Monte Carlo simulations are useful for predicting the response of detectors to different radiation sources. Simulations of GCD1 have been performed previously by the LANL group using ACCEPT, an integrated tiger series Monte Carlo code, and compared to experiment with good agreement.[3] Recently, complementary work has commenced using GEANT4, a three-dimensional particle physics code developed by contributing groups, such as CERN and SLAC.[8] A visualization of the GCD1 geometry is shown in Fig. 2.

Initial work involved benchmarking the two codes using matching parameters, for a configuration where ACCEPT had previously been compared with experiment. The Cherenkov

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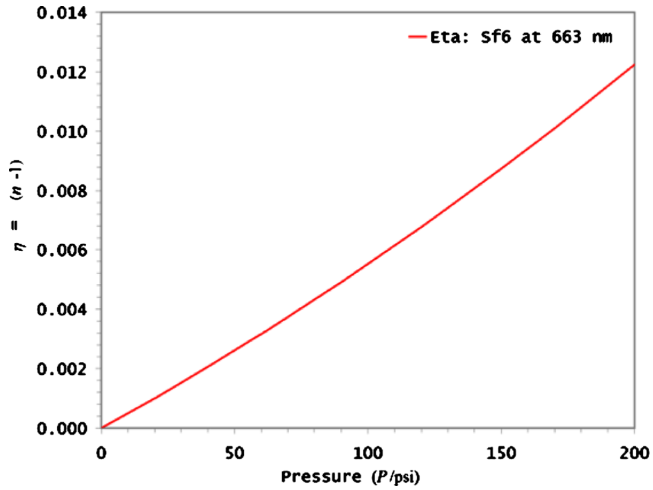

FIG. 1. (Color online) The SF_6 eta as a function of the gas pressure.

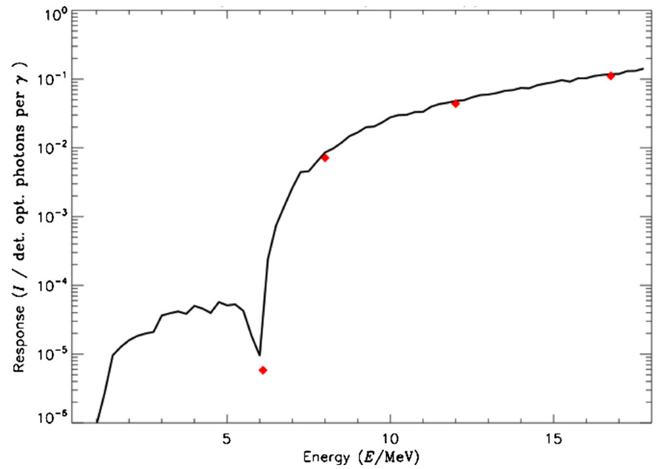

FIG. 3. (Color online) GCD1 response as a function of incident γ energy at 100 psi CO_2. ACCEPT shown as diamonds and GEANT4 shown as continuous line.

threshold analysis discussed earlier was an appropriate area to study.

IV. INTENSITY RESPONSE

The response of the detector is defined as the ratio of Cherenkov photons at the PMT to incident γ photons. This parameter includes Compton cross sections and Cherenkov production algorithms and transport. Figure 3 shows a comparison of the response as a function of incident γ energy. Both simulations were CO_2 at 100 psi. The response and threshold region compare well between 6 and 18 MeV. The threshold γ energy also agrees with Eq. 1, which predicts a value of 6.05 MeV for an index of 1.0033. Below 6 MeV, a response is observed in the GEANT4 simulation that is not present in ACCEPT. Further investigations confirm that this originates from the Cherenkov emission of electrons in the glass PMT window. A temporal constraint will be used in the future to separate response from glass background. At the 16.72 MeV DT fusion energy, GEANT4 response is measured as 0.119 γ_{Ch}/γ_{DT}, this is 6.25% greater than the ACCEPT value and likely due to the differences in Compton cross sections.

V. TEMPORAL RESPONSE

A further investigation was made into the response of the diagnostic to a monodirectional and monoenergetic source of gammas; this yields the temporal response function. GEANT4 and ACCEPT temporal responses are shown in Figs. 4 and 5, respectively. The width of the signal is due to the numerous possible electron scattering tracks, Cassegrainian path separation, and photon time of flight separation due to dispersion. At the time of writing, temporal profiles recorded by GCD1 are dominated by the spreading from the microchannel plate (MCP) based PMTs, and the RH, with FWHMs an order of magnitude greater than the detector. There is, however, RH information encoded at the picosecond regime, necessitating the development of faster technology. Current MCP technology is required for its high gain, allowing weak DT signals to be amplified by 10^6 at Omega with total neutron yields of 10^{13}. At the National Ignition Facility (NIF) where total neutrons yields are predicted to be up to 10^{19}, streak cameras with FWHM $\sim$5 ps, could be used with low gain. Consequently, the temporal spreading of the diagnostic will increase in significance.

VI. THIN DISK EXPERIMENTS AT OMEGA

At NIF, the mechanism for imploding capsules is indirect and utilizes secondary heating processes through the use of a *Hohlraum*. *Hohlraum* materials are Au, U, Be, and several trace elements. The RH will now be perturbed by neutron interactions with *Hohlraum* materials subsequent to the implosion. Experiments involving thin disks $\sim$6 cm in front of GCD1, have been performed at Omega to predict the impact of secondary interactions.[9] The disks are located such that $(n,n'\gamma)$ signals are observed 1 ns after the DT signal. A

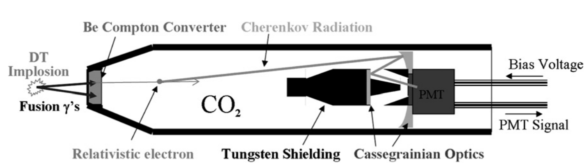

FIG. 2. Schematic view of the GCD Cherenkov detector fielded at the Omega laser facitity.

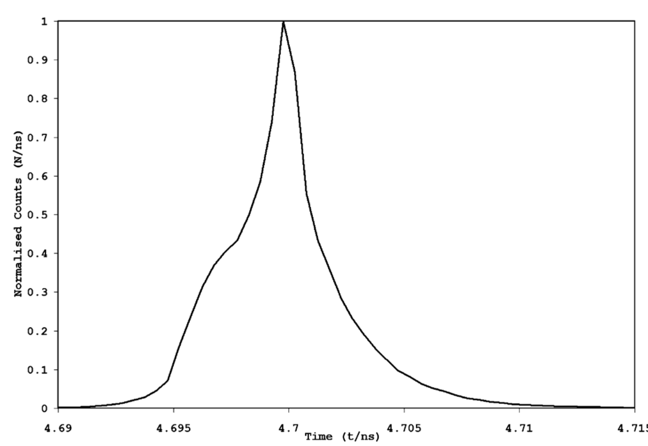

FIG. 4. GCD1 temporal response function simulated using GEANT4 at ca. 3 ps FWHM.

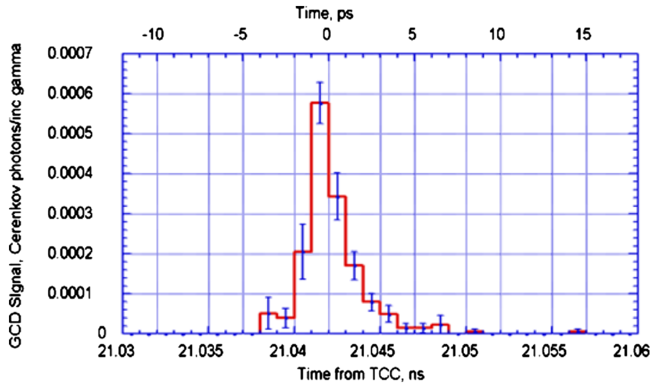

FIG. 5. (Color online) GCD1 temporal response function simulated using ACCEPT at ~2.5 ps FWHM.

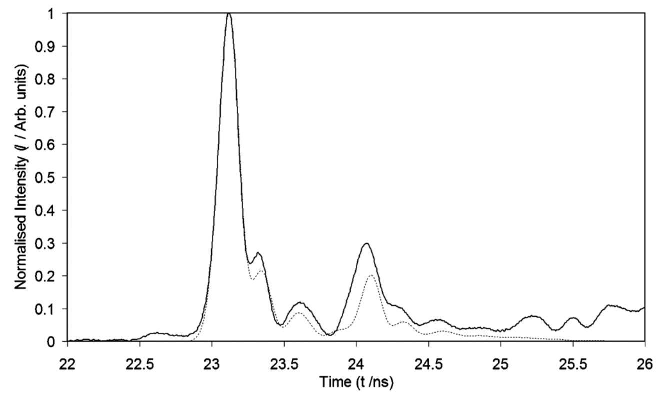

FIG. 6. Omega silicon disk data (continuous) compared to GEANT4 simulation (dashed).

GEANT4 geometry was implemented and compared with the experiment for many materials, Si is shown in Fig. 6.

The increasing Omega data commencing at 25 ns are due to $(n,n'\gamma)$ from target chamber objects absent in the GEANT4 simulation. Agreement between experiment and simulation is reasonable, with the simulation predicting the secondary intensity 37% lower; however, this was not true for all materials. Be, C, and O emitted gammas with energy exceeding predictions from conservation laws. This has been identified by the GEANT4 committee and is under investigation. With appropriate examination of the γ spectra, GEANT4 has proven to be a useful tool for simulating secondary gamma experiments at Omega.

VII. DISCUSSION

GEANT4 has been demonstrated as a powerful tool for simulating diagnostics at Omega and in the future, NIF. Simulations have been performed to predict the Cherenkov intensity and timing response of GCD1 fielded at Omega; subsequent comparison with the experimentally validated ACCEPT code shows good agreement.

Calculations have commenced for Gamma Reaction History (GRH), the next generation Cherenkov detector to be fielded at NIF during the ignition campaign, 2010.[10] ACCEPT and GEANT4 will be invaluable tools for predicting the signal intensities and profiles, and optimizing detector parameters.

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