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Extended performance gas Cherenkov detector for gamma-ray detection in high-energy density experiments[a)]

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A new Gas Cherenkov Detector (GCD) with low-energy threshold and high sensitivity, currently known as Super GCD (or GCD-3 at OMEGA), is being developed for use at the OMEGA Laser Facility and the National Ignition Facility (NIF). Super GCD is designed to be pressurized to ≤400 psi (absolute) and uses all metal seals to allow the use of fluorinated gases inside the target chamber. This will allow the gamma energy threshold to be run as low at 1.8 MeV with 400 psi (absolute) of C_2F_6, opening up a new portion of the gamma ray spectrum. Super GCD operating at 20 cm from TCC will be ∼400 × more efficient at detecting DT fusion gammas at 16.7 MeV than the Gamma Reaction History diagnostic at NIF (GRH-6m) when operated at their minimum thresholds. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4892553]

I. INTRODUCTION

Gas Cherenkov Detectors (GCD)[1,2] have proven quite useful in measuring multi-MeV gamma rays produced in laser-based inertial confinement fusion (ICF) experiments. They provide the time of peak nuclear reactivity, temporal burn width, absolute thermonuclear yield, and shell rho-R measurements, all with good accuracy. GCDs operate by converting MeV gammas to UV/visible photons for easy detection. They provide variable energy thresholding, based on pressure and temperature of the Cherenkov-conversion gas, and fast time response (∼10 ps) which then gets limited by the photomultiplier and signal transmission line responses (to ∼100 ps).

GCD instruments are deployed at both the Omega Laser Facility[3] and the National Ignition Facility (NIF)[4] and routinely acquire high-quality data for a variety of experiments. Currently, there are 2 coaxial GCDs fielded on OMEGA that are designed to be inserted into ten inch manipulators (TIM) so that they can be placed close to an imploding capsule (≥10 cm) for maximum solid angle collection of gammas. These GCDs are limited to ≤100 psi (absolute) of pressure by design, and are not allowed to contain fluorinated gases due to the use of O-ring seals which increase the risk of leakage and hence possible corrosion of the tritium purification system on OMEGA. Because the energy threshold is determined by the index of refraction of the gas contained in the unit, and therefore the pressure (as well as temperature), the energy threshold is limited to ≥6.3 MeV with CO_2. Additional GCD-type detectors, known as Gamma Reaction History[5] (GRH), operate at OMEGA and NIF.

The GRH-6m consists of four identical GRH units mounted outside the NIF target chamber at 6.07 m from target chamber center (TCC) so as to not compete for limited diagnostic insertion manipulator (DIM) access. GRH is limited to <215 psi (absolute), and is allowed to operate with fluorinated gases such as SF_6, lowering the Cherenkov conversion threshold to ≥2.9 MeV. The improved lower threshold enables ablator areal density measurements based on the ^{12}C(n,n′) gamma at 4.44 MeV.

A new GCD is needed with greater sensitivity and a lower energy threshold. The greater sensitivity is reached by operating inside the OMEGA or NIF target chamber. A lower energy threshold is reached by increasing the gas pressure and designing the GCD to contain fluorinated gases. Super GCD (or GCD-3 at OMEGA) is designed to be pressurized up to 400 psi (absolute) and uses all metal seals to allow the use of fluorinated gases. With this instrument, the energy threshold can be as low as 1.8 MeV, opening up a new portion of the gamma ray spectrum to investigation. Super GCD operating at 20 cm from TCC will be ∼400 × more efficient at detecting DT fusion gammas at 16.7 MeV than GRH-6m at NIF when operated at their minimum thresholds. Hence, it will prove quite useful for providing reaction histories in experiments for which GRH-6m is too insensitive, such as separated reactant mix studies consisting of tritium-filled CH targets containing CD layers. It will also allow the detection of dim,

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low-energy gammalines, such as the 5.5 MeV line arising from HD fusion.

II. DESIGN FEATURES

The primary goals of the Super GCD are: (1) achieve an energy threshold as low as reasonably achievable, (2) improved signal-to-noise (SNR) relative to previous GCD designs, and (3) incorporation of an optical timing fiducial. Constraints imposed by the OMEGA Laser Facility forced several new design features. The differences between GCD-3 and the existing GCD-1 are depicted in Figure 1.

The first goal required a survey of gas properties to find the gas that would give the highest index of refraction (n), and hence the lowest Cherenkov threshold, while also being relatively benign (i.e., nontoxic and nonflammable). SF_6 was chosen for GRH for its exceptionally high n at a given pressure, however, SF_6 has an equilibrium vapor pressure of ∼320 psi (absolute) at room temperature. Thus, the maximum operating pressure in GRH was restricted to 215 psi (absolute) to avoid condensation in the gas cell, producing a 2.9 MeV Cherenkov threshold limit. Our survey revealed a better alternative, C_2F_6, which has an equilibrium vapor pressure of ∼430 psi (absolute). Hence, the GCD-3 is designed to a maximum operating pressure of 400 psi (absolute), reducing the threshold to 1.8 MeV.

The biggest drawback of using a fluorinated compound is that it can dissociate at high temperature, producing atomic fluorine which has the potential to corrode the catalyst within the tritium purification system. For this reason, the OMEGA facility imposed the stringent leak rate requirement of $<1 \times 10^{-9}$ scc/s at 1 atm He (i.e., 1 cc per 32 years). This necessitates the use of all-metal seals since o-rings cannot meet this specification. To ensure durable, reusable seals, the sealing surface needs to be stainless steel. In addition, the high-pressure sapphire window used to transmit Cherenkov light from the gas cell to the photomultiplier tube (PMT) needs to be brazed into a small stainless steel flange.

The next constraint is that the GCD must weigh no more than 100 lb to be fielded in the OMEGA TIM (or 125 kg for a NIF DIM). This rules out the use of stainless steel as the pressure vessel material. The solution was to use lightweight aluminum for the pressure vessel and explosion-bonded bimetallic aluminum-to-stainless steel flanges.

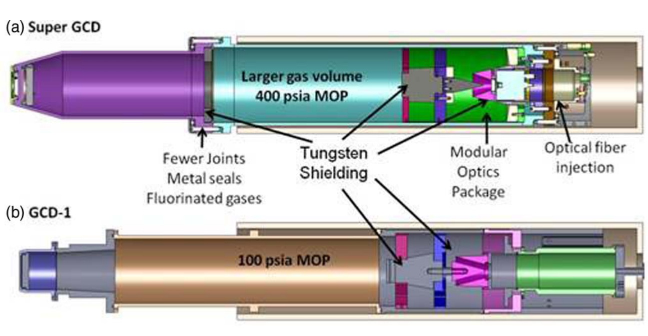

FIG. 1. CAD model depicting differences between the (a) Super GCD and (b) GCD-1. Each gas cell is approximately 1 m long.

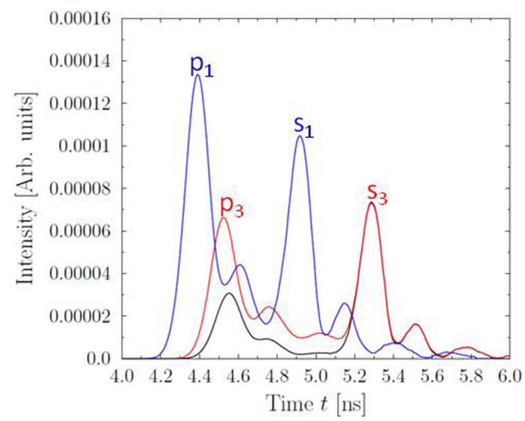

FIG. 2. Simulated signals for GCD-1 and GCD-3 at 14 MeV threshold. The undesired precursor (p_1) is dominant for GCD-1 (blue) and overlaps with the Cherenkov signal (s_1). The precursor (p_3) is significantly reduced for GCD-3 (red) and the signal (s_3) is delayed an additional 0.25 ns so as to minimize overlap. The addition of a forward shield ring reduces the p_3 precursor further (black) without affecting s_3, allowing the precursor to essentially return to baseline prior to s_3.

The goal of improving SNR precipitated a redesign of the collection optics and the shielding. Figure 2 depicts simulated GCD-1 and GCD-3 signals at 14 MeV threshold from GEANT4.[6] An issue that is particularly prevalent at high threshold, or low gas pressure, in GCD-1 (blue curve) is the existence of a precursor signal (p_1) whose ringing tail interferes with the main Cherenkov signal (s_1). This precursor is the result of gammas scattering off gas cell components, as well as the resulting electrons from this gamma-scattering, reaching the PMT on a nearly direct path from TCC and producing gas-pressure-independent signal. Cherenkov photons on the other hand must follow the folded optical path defined by the Cassegrain reflector configuration which delays them by approximately 0.5 ns relative to the direct path. This time is insufficient for the PMT ringing pattern of the precursor signal to return to baseline prior to the arrival of the Cherenkov signal. In GCD-3, the primary mirror has been moved farther away from TCC to add an additional ∼0.25 ns of delay between p_3 and s_3. Care was taken to not delay the signal any more than necessary in order to avoid overlap with later precursor signals caused by neutron-induced gammas coming from mass in close proximity to TCC, such as x-ray imaging snouts and the neutron temporal diagnostic (to avoid interference, proximity masses should be kept >8 cm from TCC). By adding a ring of hevimet tungsten-alloy shielding to the region just behind the front flange of GCD-3 (Figure 1), the precursor (black curve below p_3) is reduced without affecting the Cherenkov signal (s_3). Although it appears that the GCD-3 Cherenkov signal is ∼20% smaller than that of GCD-1, additional optical modeling indicates that the combination of slightly larger solid angle of the gamma-to-electron convertor, enlarged gas volume, larger reflective area of the primary mirror, and an aspheric secondary mirror result in GCD-3 being at least 20% more sensitive than GCD-1. It is expected that this result will be borne out when GCD-1 and GCD-3 are operated simultaneously at the same threshold for the first time.

III. DETECTOR RESPONSE

The most significant advantage of GCD-3 relative to GCD-1 is that it will operate at significantly lower Cherenkov threshold. Figure 3 depicts detector sensitivity in terms of the number of Cherenkov photons estimated to reach the photocathode of the PMT per source gamma ray launched from TCC. The GCD detectors are both placed at 20 cm from TCC, as is customary at OMEGA, while the GRH-6m is placed at 6.07 m to represent the NIF configuration. When GCD-3 is pressurized with 100 psi (absolute) CO_2, the limiting value for GCD-1, its sensitivity is about 20% higher than GCD-1. However, pressurization to 400 psi (absolute) C_2F_6 brings the threshold down to 1.8 MeV and opens a previously unexplored portion of the ICF gamma ray spectrum.

Figure 4 shows the ratios of the detector sensitivities shown in Figure 3 for each detector at its minimum threshold. Also depicted are the energies of the primary DT fusion gamma ray (DT-γ_0) at 16.75 MeV and the ^{12}C(n,n′) gamma at 4.44 MeV (^{12}C-γ). For example, GCD-3 at 1.8 MeV threshold improves response to DT-γ_0 relative to GRH-6m at 2.9 MeV threshold by nearly a factor of 400, and response to ^{12}C-γ by a factor of over 1000, owing primarily to the greatly improved solid angle of intercepted gammas. However, in order to isolate DT-γ_0 from lower energy and brighter gamma ray sources, one must typically operate at thresholds in the 4.5–10 MeV range (depending on capsule material and whether there is a hohlraum).

The final goal is to precisely time Cherenkov signals relative to laser timing by injection of a 2ω (527 nm) comb fiducial from the front end of the laser that mixes with the optical signal upstream of the PMT. In this way, PMT transit time variations as a function of tube bias and variations amongst individual tubes does not add to timing uncertainties. A VCR connector permits incorporation of a high-pressure, low-leak optical feedthrough coupled to an optical fiber that reflects 2ω light off the secondary mirror. A means of attenuating the 2ω fiducial with PMT gain will be provided to maintain the amount of charge drawn from the PMT within a specified range without shifting the timing of the fiducial.

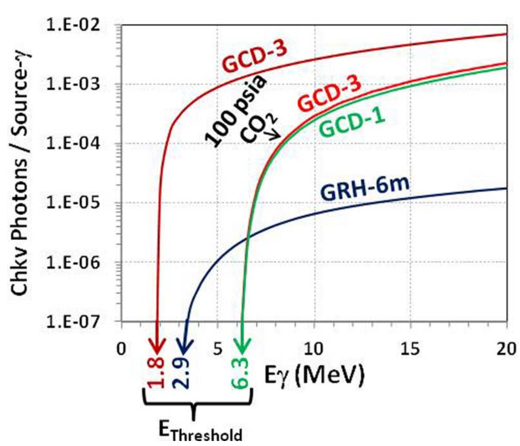

FIG. 3. Detector sensitivity for GCD-1 and GCD-3, both placed at 20 cm from TCC, and GRH-6m at 6.07 m from TCC at NIF, for several different Cherenkov thresholds.

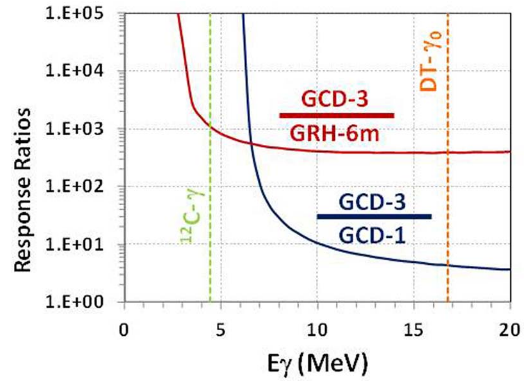

FIG. 4. Ratio of detector sensitivities with each detector at its minimum threshold (its maximum pressure).

An additional feature is the ability to mount samples ("pucks") of different materials off the front of the nose cone, placing the puck face approximately 6 cm from TCC so that neutron-induced gammas from the puck are delayed about 1 ns relative to fusion gammas owing to the difference in speed between 14.1 MeV DT fusion neutrons and gammas.[7] Such pucks are used, for example, to calibrate the detector response against carbon gammas so that accurate CH ablator areal density measurements can be made.[8]

IV. CONCLUSION

GCD-3 will support an array of on-going and future High Energy Density Physics (HEDP) experiments which can benefit from enhanced gamma ray detection. In addition to measurement of the weak fusion gammas yet to be detected or be better characterized at ICF conditions (e.g., HD, DD, D^{3}He, T^{3}He, TT, etc.), it will help in studies of fuel/shell mix and charged-particle stopping power. At NIF, 4 GRH gas cells are used to perform crude differential spectroscopy of the gamma-ray spectrum. Additional GCD-3 gas cells, whether at OMEGA or NIF, will enhance this capability, particularly at the low-energy end of the spectrum. For NIF, Super GCD will likely require additional shielding modifications to account for the dramatically increased x-ray background associated with indirect-drive. However, the eventual goal is to measure resolved gamma-ray spectra with either a Compton Spectrometer with magnetic dispersion (GEMS),[9] or a Single-Hit Pixelated Detector (Furlong).

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