Design and Construction of a Gamma Reaction History Diagnostic for the National Ignition Facility

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Abstract. Gas Cherenkov detectors have been used to convert fusion gammas into photons to record gamma reaction history measurements. These gas detectors include a converter, pressurized gas volume, relay collection optics, and a photon detector. A novel design for the National Ignition Facility (NIF) using 90° off-axis parabolic mirrors efficiently collects signal from fusion gammas with 8- ps time dispersion. Fusion gammas are converted to Compton electrons, which generate broadband Cherenkov light (response is from 250 to 700 nm) in a pressurized gas cell. This light is relayed into a high-speed detector using three parabolic mirrors. The relay optics collect light from a 125-mm-diameter by 600-mm-long interchangeable gas (CO₂ or SF₆) volume. The parabolic mirrors were electroformed instead of diamond turned to reduce scattering of the UV light. All mirrors are bare aluminum coated for maximum reflectivity. This design incorporates a 4.2-ns time delay that allows the detector to recover from prompt radiation before it records the gamma signal. At NIF, a cluster of four channels will allow for increased dynamic range, as well as different gamma energy thresholds.

1. Introduction

The original Gas Cherenkov Detector (GCD) was fielded at the Laboratory for Laser Energetics (LLE) OMEGA laser facility to record gamma reaction history measurements. These gas detectors include a converter, pressurized gas volume, relay collection optics, and a photon detector. A novel design for the National Ignition Facility (NIF) using 90° off-axis parabolic mirrors efficiently collects signal from fusion gammas with 8-ps time dispersion. Fusion gammas are converted to Compton electrons, which generate broadband Cherenkov light (response is from 250 to 700 nm) in a pressurized gas cell. This light is relayed into a high-speed detector using three parabolic mirrors. The relay optics collect light from a 125-mm-diameter by 600-mm-long interchangeable gas (CO₂ or SF₆) volume. The parabolic mirrors were electroformed instead of diamond turned to reduce scattering of the UV light. All mirrors are bare aluminum coated for maximum reflectivity. This design incorporates a 4.2-ns time delay that allows the detector to recover from prompt radiation before it records the gamma signal. At NIF, a cluster of four channels will allow for increased dynamic range, as well as different gamma energy thresholds.

Because the GCD was light starved, it was moved close to the gamma source. Its position required penetration inside the OMEGA target vacuum chamber. Because of where the GCD detector is located, prompt gammas induce a precursor signal that is 0.5 ns ahead of the Cherenkov light. Tungsten shielding reduces the amplitude of this precursor signal.

The new gamma reaction history (GRH) diagnostic is external to the target chamber, requiring no chamber penetrations [2] [3]. There is no requirement to position the GRH at precise position from the gamma source. Just as in the original GCD, gammas from fusion reactions are converted to Compton
electrons that are converted into Cherenkov photons. The Cassegrain optics are replaced with three 90°
off-axis parabolic (OAP) mirrors to relay the light into a high-speed detector.

Because light is collected from source locations throughout a gas volume, the GRH detector is
positioned at the stop position rather than at an image position. The stop diameter and its position are
independent of the light-generation locations throughout the gas cell. This parabolic mirror relay is
functioning as a non-imaging system. Because of the UV wavelength requirement, the parabolic
mirror surface must be smooth to limit scattering.

2. Optical and Optomechanical designs

Figure 1 shows how light is collected into the detector. This example ray tracing shows five γs
originating from a point at the target chamber center (TCC) that hit five field positions on the
converter, producing Compton electrons at −2, 0, and +2 degrees. Here, Cherenkov light is emitted
along each of these electron trajectories, and the detector collects light within a ±1-degree cone
centered about each electron trajectory. The high-speed detector has a 1-cm collection area. The
combination of OAP2 and OAP3 are used to demagnify the first stop diameter. Due to the 10 to 1
demagnification of the first stop onto the second stop (detector), the detector collection angle is
limited to ±3 degrees of the source light, which can be summed up from any combination of electron
and photon angles (shown here are ±2-degree electrons and ±1-degree photons).

Figure 1. Cherenkov light is generated throughout the gas cell. Shown is optical ray
tracing from one of many source planes.

Figure 2. This new GRH diagnostic is external to the NIF target chamber. Optical fibers provide dry
run and calibration signals.

Figure 2 shows the mounting hardware supporting the OAPs. The support structure is not shown.
The A1 converter measures 5 inches in diameter by 15-mm thick. Tungsten (W) shielding protects
both the detector and the pressure window from line-of-sight and scattered radiation. A Mach-Zehnder
(MZ) modulator transmits the data by optical fibers to a remote location and preserves signal
bandwidth [4]. There is an air gap spacing between the chamber port and the converter housing. The
OAP layout delays the Cherenkov light by 4.2 ns to enable the detector to recover from prompt
gammas. Expected burn width of fusion is less than 1.5 ns. The temporal response of the optical
system is limited by the dispersion of the sapphire pressure window to 8 ps over the wavelength range
of 250 to 700 nm. Gammas will produce Cherenkov light in the sapphire pressure window, but the
light goes the wrong direction due to the layout of the OAPs. Figure 3 shows a 3-D perspective of the
mounting structures. The port cover is removable to exchange convertors or replace with an X-ray
scintillator.

Optical ray tracings demonstrate how light can be collected from different angled trajectories of the
Compton electrons as they traverse the gas volume. A Monte Carlo physics model of the conversion
process from gammas to Cherenkov photons is used to generate photon trajectories. The collection

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efficiencies for different gamma energies that produce different electron angles are evaluated. Figure 4 shows an example of the ray counting from a set of photon trajectories produced inside a 100 psi CO$_2$ gas volume. Of the 10,000 photons that are generated by this Monte Carlo run, 524 usable photons make it into the detector. This demonstrates the challenge of collecting photons.

Inside the GRH enclosure, optical fibers insert light in two directions through a hole at the center of the turning mirror (see figure 2). This provides both calibration and dry run signals. A drive laser timing fiducial (FIDU) points directly at the detector (forward direction). Three fibers point towards the converter (backwards direction) and reflect their light off the converter to simulate a dry run light source starting from the converter plane. An additional target chamber light monitor signal collected by an optical fiber is multiplexed with the FIDU signal.

The problem with using relay optics with a volume source of light is that as the object position moves, the image position also moves. However, the stop position never moves and its diameter does not change, as its diameter is related to the full angle cone of light collected. The stop position is the best location to place a detector that is collecting light from many object source planes.

The parabolic mirrors were electroformed nickel mirrors instead of diamond-turned aluminum mirrors to reduce scattering of the UV light [5]. All mirrors are bare aluminum coated for maximum reflectivity at wavelengths below 400 nm. Because the amount of light scattered from a surface varies as the square of the ratio of surface roughness to wavelength, diamond turned OAPs will not work in the UV. We confirmed this formula by photographing the scattering at two different wavelengths on prototypes of both the electroformed nickel mirrors and the diamond-turned mirrors.

The optical alignment operation is fairly simple. Crosshairs are placed at the converter position. The detector is replaced with a grid pattern. The turning mirror has tilt adjustments. The hole in the turning mirror is tilted to line up with the cross hairs and grid pattern, sighted by eye. If alignment is not perfect, then a different set of rays are collected at the detector. The variation of ray count with misalignments is shown in figure 5, and demonstrates alignment sensitivity for the detector and the turning mirror. Figure 5 shows that the best z-axis position of the detector needs further optimization.

Double O-ring seals are used for both pressure and RF. The GRH enclosure prevents high-frequency electrical noise from affecting the photomultiplier tube (PMT) detector and associated electronics. The electrical noise can originate both from the environment and also from electron generation inside the gas cell. This enclosure has no welded parts. The external noise was blocked by making the enclosure electrically continuous with conductive O-rings. Chomerics Cho-seal 1285, a silicon O-ring impregnated with silver-plated aluminum, was used. The RF cavity resonances within this enclosure are damped with a magnetically loaded absorbing rubber. All enclosure surfaces were treated with a chemical conversion coating per MIL-D05541 class 3, which provided anti-corrosion.

![Figure 3.](image1.png) Component labeling of the GRH used at the LLE OMEGA. A Mach-Zehnder modulator transmits data to a remote location.

![Figure 4.](image2.png) Monte Carlo rays derived from simulation code show that we collect 5.2% of Cherenkov light.
protection and maximum electrical conductivity. Inside wall surfaces of the GRH were made to absorb light using a black Aeroglaze 300 series coating for vacuum systems, which does not outgas. Viton O-rings provide the pressure seal.

3. GRH installation on NIF
The initial NIF installation will have four GRH units, each set to a different gas pressure for detecting gammas ranging from 3.5 MeV to 20 MeV. For example, 200 psi of SF₆ gives a 3.5-MeV Cherenkov threshold, and 100 psi of CO₂ gives a 7-MeV Cherenkov threshold. [2] Each of the four units is attached to a support frame, as in figure 6. This frame is attached to a NIF chamber port. The four detectors are arranged into the middle of the cluster so they experience the same shielding environment. There is an 8-inch air separation between the chamber port and converter housing. The converter can be replaced with an X-ray scintillator when we record timing signals produced by the NIF drive lasers hitting a gold ball instead of a fusion capsule. The complete system attached to the port weighs 1500 lb. Design requirement for initial installation at NIF is to detect gammas emitted from fusion burns producing 10¹⁴ to 10¹⁶ neutrons and a system response time of 100 ps.

Numerous recording hardware components must be calibrated and maintained. Several high-bandwidth oscilloscopes with different time records archive the MZ signals [4]. Optical fibers feed light signals into each GRH unit. They supply both dry run and calibration signals. Another fiber looks through a small window at the center of this NIF port. This chamber light fiber provides an exact timing FIDU of the drive laser hitting target chamber center and, with a suitable fiber loop delay, this FIDU is added to the GRH data record.

**Figure 5.** Optical illumination program optimizes the light collection efficiency of the detector.

**Figure 6.** NIF will have four GRH units, each with a different gas pressure, for detecting gammas of several energy levels.

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