A Reduced Model for the ICF Gamma-Ray Reaction History Diagnostic

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Abstract. An analytic model for the gamma reaction history (GRH) diagnostic to be fielded on the National Ignition Facility is described. The application of the GRH diagnostic for the measurement of capsule rho-R during burn using 4.4 MeV carbon gamma rays is demonstrated by simulation.

1. The forward model

A forward model for the gamma reaction history (GRH) diagnostic [1] has been developed to simulate the output voltage waveform for typical low yield shots on NIF. The photo-electronic signal has the form

\[ N_e = \eta_n \eta_e \left\{ \delta \eta_{\gamma} \rho_{\gamma} N_{\text{tot}} \left( \frac{D_4}{4R_A} \right)^2 \sqrt{\frac{4 \ln 2}{\pi \tau_{\text{FWHM}}^2}} e^{-4 \ln 2 (t - t_{\text{FWHM}})} \right\}^{1/2} \]

where \( N_e \) is the electron number as a function of time, \( N_{\text{tot}} \) is the integrated neutron yield of the shot (typically \( 10^{14} - 10^{16} \)) and the rest of the system variables are defined in Table 1. When the sampling bin probability is greater than unity, we use a Gaussian noise model given by

\[ \tilde{N}_{\sigma} = \text{INT} \left\{ \delta \eta_{\gamma} \rho_{\gamma} N_{\text{tot}} \left( \frac{D_4}{4R_A} \right)^2 \sqrt{\frac{4 \ln 2}{\pi \tau_{\text{FWHM}}^2}} e^{-4 \ln 2 (t - t_{\text{FWHM}})} \right\}^{1/2} \text{erfi}(\text{rand}) \]

and if we are in a Poisson regime when the probability is less than one, we use

\[ \bar{N}_{\sigma} = \text{INT} \left\{ \delta \eta_{\gamma} \rho_{\gamma} N_{\text{tot}} \left( \frac{D_4}{4R_A} \right)^2 \sqrt{\frac{4 \ln 2}{\pi \tau_{\text{FWHM}}^2}} e^{-4 \ln 2 (t - t_{\text{FWHM}})} \right\}^{1/2} \text{erfi}(\text{rand}) \]

where \( \text{erfi}(\text{rand}) \) is the inverse error function of a random number between 0 and 1, (yielding a Gaussian distributed noise amplitude with a mean of zero and standard deviation of unity) and INT

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generates an integer of the argument. For an integrated neutron shot yield, \( N_{\text{tot}} = 2 \times 10^{14} \) (i.e. a low yield THD shot), a peak gamma flux rate of over \( 10^3 \) J/s-ps will occur at \( t = t_B + t_{\text{TOFC}} \) yielding Gaussian statistics for a \( \sim 5 \) ps sample time during the main part of the pulse. The value for the conversion efficiency of gamma rays (striking the converter plate) into productive electrons that enter the detector gas, \( \eta_e \), has been determined using the ACCEPt code [2].

Similarly, the electrons in the gas generate productive Cherenkov photons with an efficiency, \( \eta_{ec} \), given by the ACCEPt code. The Cherenkov photons hit the microchannel plate (MCP) and generate photoelectrons in the MCP with efficiency, \( \eta_e = 0.17 \). This signal (with noise) is further amplified by the gain of the single stage MCP tube and circuit, \( G_{\text{MCP}} \). However, the temporal response of the MCP to a single photon is neither instantaneous nor prompt. For the Photek/AWE system, the response function is dominated by a \( \tau_c = 135 \) ps FWHM Gaussian transfer function followed by a ringing tail, as shown in Figure 1. This response width will be reduced to 90 ps for the NIF system (shown in black in Figure 1).

**Table 1.** GRH model parameters.

| Variable Name | Definition | Nominal value |
|---------------|------------|---------------|
| \( R_{Jn} \) | Branching ratio of DT \( \gamma \)’s versus neutrons | \( 2 \times 10^{-5} \) |
| \( t_B \) | Implosion bang time | 0 |
| \( t_{\text{FWHM}} \) | Implosion full width half max burn width | 100 ps |
| \( D_A \) | GRH converter plate diameter | 12.7 cm |
| \( R_A \) | Target chamber radius | 590 cm |
| \( t_{\text{TOFC}} = R_A/c \) | Time of flight delay to GRH converter plate | 19.7 ns |
| \( \eta_e \) | Efficiency of \( \gamma \)'s to Compton e’ | \( 8 \times 10^{-3} \) |
| \( t_{\text{c}} \) | Conversion time delay in convertor plate | 50 ps |
| \( \eta_{ec} \) | Conversion efficiency of e’ to Cherenkov photons | 25 |
| \( t_{\text{gas}} \) | Average electron and photon time delay in the gas cell | 2 ns |
| \( \eta_{eo} \) | Efficiency of Cherenkov photons to MCP circuit e’ | 0.17 |
| \( G_{\text{MCP}} \) | Electronic gain | 10,000 |
| \( \delta t \) | Digitization time | \( 4.89 \times 10^{-12} \) s |
| \( R_O \) | Oscilloscope load resistance | 50 \( \Omega \) |
| \( V_{\text{rms}} \) | Electronic noise rms amplitude | 30 mV |

**Figure 1.** Measured GRH response function for 135 ps (red) and a scaled 90 ps response.

**Figure 2.** Simulated GRH voltage output using the 90 ps PMT response curve of Figure 1.

The binned temporal electron number density signal, \( N_j \), out of the MCP is the convolution of the signal into the MCP and the MCP response function, \( H(t) \), given by

\[
N_j(t) = \int_{-\infty}^{\infty} d\tau N_j(\tau) H(t - \tau) = N_j(t) * H(t)
\]
where the "*" represents the convolution. Since $N_s$ represents the electron signal for each $\Delta t$ sampling bin, we can calculate the current and voltage as

$$V(t) = I(t)R_{\Omega} = qR_{\Omega} \frac{N_s}{\Delta t} \approx 1.6 \times 10^{-6} N_s.$$  

Simulated output for a 100ps Gaussian burn profile is given in Figure 2.

### 1.1 Arbitrary Dark Current Noise Model

Noise in the amplification chain is modelled by adding a scaled 1/f noise spectrum to the temporal signal. The model generates a temporal realization using a frequency transform given by

$$N_{dc}(t) = \text{FFT}^{-1}\left\{ \sum_{f=f_c}^{f_{max}} \sqrt{S_N(f)} \left[ \text{erfi}(\text{rand1})e^{i2\pi\text{rand}(f)} + \text{c.c.} \right] \right\},$$

where $\text{FFT}^{-1}$ represents the inverse Fourier transform, $f_c=0.5/\Delta t$ is the cut off frequency (a.k.a. the Nyquist critical frequency) and $S_N$ is the power spectrum of the electronic noise. The variables $\text{rand1}$ and $\text{rand2}$ are two independent uniformly distributed (from 0 to 1) random numbers and erfi represents the inverse error function used to generate a Gaussian distributed amplitude.

A 1/f model routine using this form has been added to the GRH model. The spectral terms are $S_f=0$,

$$S_{n_{dc}}^{n_{max}/2-1} = \left( n\Delta f \right)^{-1/2} \text{erfi}(\text{rand}(n-1))e^{i2\pi\text{rand}(n)}$$

and

$$S_{n_{max}/2} = \left( n_{max}\Delta f / 2 \right)^{-1/2} \text{erfi}(\text{rand}(n_{max}/2-1))e^{i2\pi\text{rand}(n_{max}/2)}$$

and $S_{n_{max}}^{n_{max}/2-1} = S_n^*$, where $\text{rand}(n)$ is now assumed to be an array of length $n$ containing uniformly distributed random numbers. To calibrate this noise, the mean, $\mu$, and standard deviation, $\sigma$, of each temporal realization of noise is calculated. For our discrete temporal noise realizations, these are defined

$$\mu = \frac{1}{n_{max}} \sum_{n=0}^{n_{max}} N_{dc}(n\delta t) \quad \text{and} \quad \sigma = \sqrt{\frac{1}{n_{max}} \sum_{n=0}^{n_{max}} \left[ N_{dc}(n\delta t) - \mu \right]^2}.$$  

First the mean is subtracted out. Then the noise amplitude is set by dividing out the actual standard deviation of each temporal realization and multiplying this by the desired noise level, $V_{rms}$.

### 1.2 Background gamma model

Background gamma rays from (n,n') reactions occurring in materials surrounding the burning capsule will produce a secondary gamma signal observed by the GRH diagnostic. Most troublesome are low-Z materials close to the capsule. The capsule hohlraum is a laminated structure of radius $R_{hol}$ containing an Al cylinder. We have calculated this signal using the MCNP code, but we will not show the results in this paper. An analytical model also has been developed but has yet to be validated. We do not expect the hohlraum to be a significant GRH degradation source for NIF.

### 2. De-convolution Model

The inverse model first factors out all the conversion efficiencies of the detection chain and then performs a de-convolution to extract an approximation to the neutron production rate from the ICF shot. From the previous derivation of the forward model, the factor relating the voltage measure at the oscilloscope to the total neutron production rate of the shot is given by

$$\frac{1}{dN_n} \frac{dV(t)}{dt} = R_{\gamma n} \left( \frac{DA}{4R_A} \right)^2 \eta_{\gamma r}\eta_{\alpha}\eta_{\gamma \alpha} G_{\text{MCP}} qR_{\Omega} = 1.575 \times 10^{-24}$$
Note that we are ignoring the addition of noise and the transfer function, $H(t)$, of the electronic chain. However, we are assuming that the noise has zero mean and that the impulse response function of the electronic chain has been normalized to unity (times the amplifier gain, $G_{MCP}$, which we have included).

Besides just applying the scaling factor $F^{-1}$, a de-convolution can be performed to obtain a more accurate time profile of the gamma generation rate. Our initial model follows that of Horsfield. \[3\]. Assuming a forward model of the form

$$R(t) = F_{\text{total}} \cdot H(t) \ast E(t)$$

where $R$ is the measure temporal response profile, $H$ is the transfer function of the GRH diagnostic and $E$ is the actual gamma rate of the ICF shot. We can obtain an estimate of the gamma rate using the following

$$E_{\text{est}}(t) = \left[ 2R - R(t) \ast H(t) \right] F_{\text{total}}^{-1}$$

Followed by the iterative technique

$$E_n(t) = E_{n-1} - \alpha \left( E_{n-1} \ast H - E_{n-1} \right)$$

where this can be iterated many times and $\alpha$ is a factor less than one to maintain stability.

### 3. Extension to 4.4 MeV (n,n'γ) carbon gamma rays

Neutrons generated by D-T fusion in the ICF capsule will interact with the residual shell material on their way out of the capsule. These collisions generate 4.4 MeV gamma rays when the neutrons collide with carbon atoms in the plastic CH shell. Measurement of these gammas can provide a time-dependent measurement of the areal density, a.k.a. the rho-R, of the capsule while nuclear burn is occurring. Simulations \[4\] of the generated 4.4 MeV gamma rays have been calculated as a function of capsule rho-R and the results have been plotted in Figure 3. These results show a strong correlation between the number of 4.4 MeV gammas and capsule rho-R. LANL will be pursuing this method to improve the rho-R diagnostic capabilities of the GRH instrument for NIF.

![Image](image_url)

**Figure 3.** Gamma ray spectrum from the capsule and (b) correlation of 4.4 MeV gamma rays for a ~25% change in rho-R from a set of rad-hydro calculations using nominal THD capsule parameters.

### References

[1] Herrmann H W, et al., these proceedings.
[2] Mack J M ,  et al., 2006 Rad. Phys. Chem. 75 551 and references therein.
[3] Horsfield C J, private communication.
[4] Hoffman N M, private communication.