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A Novel Method for DT Fusion Neutron Yield Estimation Based on Measured Gamma Dose Rate for Direct Confinement Fusion (DCF) Applications Using MATLAB Graphical User Interface

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Abstract:
High-energy gamma rays generated from any form of confinement fusion experiments are an important signature for studying the dynamics of the relevant fusion processes. Due to their high energy and penetrating nature, gamma emissions are the most unperturbed fusion products, which can preserve the original information of the fusion process. Fusion gamma emissions provide a direct measure of nuclear reaction rates without being compromised by Doppler spreading, unlike neutrons. The brief overview of outcomes from studies of gamma emissions in inertial confinement fusion (ICF) presents an approach to converting a measured gamma dose rate to DT fusion neutron yields, especially for high-yield confinement experiments, such as those in direct confinement fusion (DCF) setups. This approach is our first step in developing a system of gamma diagnostics for this novel DCF-based fusion study. Though simplistic in our approach, it has provided us with a promising basis for an advanced approach to studying the dynamics of gamma emissions from a DT fusion reaction.

Keywords: *Gamma Emission, Fusion Gamma Emission, Gamma Dose Rate, Inertial Confinement Fusion, DT Fusion neutron Yield, Direct Confinement Fusion.*

1.0 INTRODUCTION

Understanding the nuclear phase of any confinement fusion reaction is necessary to improve the confinement system's design and the study of its plasma conditions. Nuclear diagnostics have played a critical role in even the early stages of confinement development. Some current examples of nuclear diagnostics include nuclear activation detectors, neutron time-of- flight spectrometers, recoil particle spectrometers, neutron imaging systems, and radiochemical diagnostics [1].

Gamma emissions generated from confinement plasmas provide unique and important information for studying the dynamics of the nuclear phase of the confinement process because the energy spectra and amount of gamma emissions produced are a direct signature of the nuclear fusion reactions themselves [1]. For example, in an ICF situation, the 16.75 MeV gamma emission line originating from the nuclear fusion reaction between deuterium (D) and tritium (T) can offer reaction history information, such as the time of peak reaction rate (i.e., bang time) and how long thermonuclear conditions are maintained (i.e., burn width). Due to their high-energy and penetrating nature, gamma emissions are the most unperturbed fusion products, which can preserve the original birth information of the fusion process.

Since the early period of confinement research, fusion gamma emission measurements have been conceived as a direct measure of nuclear reaction rates without being compromised by Doppler spreading (unlike neutrons) [1]. However, unambiguous gamma emission measurements for our new field of direct confinement study require new technological developments, which include a deepening understanding of fusion gamma emission characteristics and innovations in instrument performance.

Our venture in this wise will address these current and future challenging issues. But for us to proceed, we need to understand the progress so far made in other confinement approaches before considering their suitability or otherwise to our approaches in DCF studies.

Studies of Gamma Emissions from ICF Applicable to DCF Operations

A mixture of deuterium and tritium is mostly used in inertial confinement fusion (ICF) experiments because the DT fusion reaction is achievable at the lowest plasma temperatures. The resultant fusion neutrons are typically considered the gold standard as a yield signature for any neutronic fusion reaction, as in ICF conditions. However, it is expected that the highly compressed conditions can cause complications in accurately measuring the total fusion neutron yield. The compressed capsules can be so dense that the 14.1 MeV DT fusion neutrons will scatter on their way out of the capsule and no longer represent a reliable mono-energetic peak for total yield fusion diagnostics. For example, an MCNP calculation for a compressed cryogenically layered ICF capsule (i.e., 800 mg/cm^2 of DT fuel and 400 mg/cm^2 of plastic ablator areal density) estimates that about 20% of 14.1 MeV neutrons are down scattered [2]. Furthermore, because of asymmetries in the compressed capsule, the amount of neutron scattering differs depending on the line of sight.

In contrast, the 16.75 MeV DT fusion gamma emissions are not nearly as attenuated (3%) as 14.1 MeV fusion neutrons (20%) based on the MCNP simulation and, therefore, can provide a reliable alternative for total fusion yield measurements [2]. Gamma emissions offer the potential of having one detector in one location, giving the spatially averaged total yield, avoiding the complications of the neutron measurements.

Due to its relatively large cross section, the reaction $D(T,n)^4He$ is considered to be among the most promising to focus upon for the purposes of fusion energy research [3]. As such, DT implosions constitute the majority of experiments performed at ICF facilities and neutrons from this reaction are studied intensively. Gamma rays from the branch $D(T,\gamma)^5He$ are produced simultaneously and are also used for complementary diagnostic purposes in fusion energy focused implosion experiments. In particular, the DT gamma is currently used for measurements of burn width, which is considered a vital parameter in evaluating the performance of these implosions. Gammas from this reaction are additionally used in dedicated experiments that seek to study the mix of ablator material from the target's shell into its hot spot, where most of the fusion occurs, as excessive mixing of ablator material into the hot spot is known to degrade overall implosion performance [4]. In addition to their importance to ICF itself, the study of the gammas from these reactions serve as references for the design and execution of experiments that instead seek to perform nuclear measurements using implosions at facilities such as OMEGA or the NIF. The DT gamma is also vital for the absolute calibration that is necessary to make such measurements.

In addition, the principles of gamma-ray diagnostic techniques have been described elsewhere [5, 6]. Three types of nuclear reactions that may be noted for gamma diagnostics are: reactions between fuel nuclei (H, D, T, ^{3}He), interaction between fast charged particles (p, d, t, α, ^{3}He) and plasma impurities (^{9}Be, ^{12}C) and reactions with specially doped impurities (^{10}B, ^{11}B, ^{7}Li) [7].

Furthermore, the Gamma Detector Response and Analysis Software (GADRAS) which is a sophisticated tool used primarily in the field of nuclear science and engineering as well as in nuclear security and safety monitoring and studies, has capabilities that include amongst others, estimating source energy distributions from measured spectra. Furthermore, it includes a tool that enables the computation of gamma-ray and neutron dose rates based on either radiation source models or measured spectra. For the model-based computation of dose rates, the distance between the source and the detector as well as the source activity must be specified. Spectrum-based dose calculations give the dose at the detector location without regard to the type of gamma-ray source and the distance of the detector from the source [7].

The ability to accurately simulate gamma spectra from materials that emit both neutrons and gammas is very important to the analysis of special nuclear materials e.g., uranium and plutonium [8]. The approach presented in the GADRAS documentations of [9] uses MCNP neutron/photon transport simulations coupled to GADRAS detector response calculations to produce realistic estimates of the full gamma spectrum, including full-energy peaks, Compton continua and other features.

Rather than the complicated approaches involving the complex and often difficult to obtain MCNP and the use of GADRAS that are based on ICF studies, an easier and simpler approach will be the use of commonly available MATLAB to design a GUI-based standalone app that can provide all measurement and research results devoted to the Direct Confinement Fusion (DCF) environment since the difference between the ICF and DCF is only in the confinement mode and not in the products of the confinement methods. Here, all experimental and mathematical derivations applicable to the ICF can easily be modified and applied to the DCF.

Direct Confinement Fusion (DCF) [10]

The Direct Confinement Fusion (DCF) structure is designed to heat up and maintain reactants in a plasma state in order to enable fusion through quantum tunneling. The design employs direct heating of the fusion generator by enclosing it in a silica blanket. Here, the heat supplied to the base of the design is transmitted to the attached heating plates. The crown, which contains the reactants, is fitted to a holding tool. Based on the Lawson Criteria, heat is supplied to the system until a Q yield of greater than 5 is achieved, where the plasma contained in the crown becomes self-sustaining. The generated heat is trapped in the upper portion of the silica blanket, and using steam in a conventional power cycle, provides electricity for commercial and other purposes [10].

The core fuel to be used in the DCF reactor is deuterium, tritium, and lithium. On one hand, deuterium, a stable isotope of hydrogen, naturally occurs in all water on Earth but at a relatively low concentration. On average, approximately 0.0156% (156 parts per million) of all naturally occurring hydrogen atoms are deuterium. This means that out of every 6,400 hydrogen atoms in water, approximately one will be deuterium. On the other hand, tritium, a key fuel in nuclear fusion reactions, can be produced through neutron bombardment of lithium, specifically lithium6, in a process known as Lithium-6 neutron absorption. Tritium generation occurs when lithium-6, an isotope of lithium, absorbs a neutron and undergoes nuclear fission to yield helium-4 and tritium [10].

In the fusion reactor, lithium is exposed to plasma in a high-temperature and pressure environment. Neutrons in the highly charged reactor core are absorbed by the lithium, thereby creating tritium. The main advantage of this approach is that it creates a supply of tritium within the reactor itself. Furthermore, as light atoms can combine to form a heavier atom and often release a neutron, deuterium and tritium can combine to release a neutron and copious amounts of energy. It is also important to note that fusion reactions can occur under extreme conditions of temperature and pressure and can involve radioactive materials. They also require specialized equipment and facilities to achieve and control. There are four basic conditions to be met for fusion to occur. Meeting these conditions is a significant engineering challenge, which our proposed DCF design meets [10].

a. High Temperature. One of the critical requirements for a fusion reaction to take place is extremely high temperature, usually in the order of millions of degrees. This high temperature provides the kinetic energy required by the atomic nuclei to overcome the natural electrostatic repulsion between them, thus enabling them to come close enough for the attractive nuclear force to take effect. The fusion generator proposed takes this factor into consideration.

b. High Pressure. High pressure or density is needed to increase the probability of collision between the atomic nuclei. It is essential because the atomic nuclei must collide with sufficient force to overcome their natural repulsion. The design of the proposed generator caters for the high-pressure conditions required for fusion.

c. Confinement Time. This refers to the length of time the fuel is kept at the necessary high temperature and pressure conditions to allow fusion to occur. The fuel must remain in these conditions for a sufficient time to ensure that more energy is released from the fusion reactions than is input to heat the fuel. The prototype being proposed caters for this feature too.

d. Plasma State. A plasma is an ionized body of positive ions and free electrons in proportions resulting in more or less no overall electric charge. It is created by heating a gas to temperatures high enough to ionize the gas molecules or atoms. The fusion generator ensures plasma with the addition of a substance that enhances quantum tunneling in the plasma state.

Mechanisms of Fusion Energy Release Applicable to the DCF

The main principle behind the release of energy that is applicable to the DCF reaction is the conversion of mass to energy. This principle is encapsulated in Einstein's famous equation $E=mc^2$, where E represents energy, m is mass, and c is the speed of light in a vacuum. This equation signifies that a small amount of mass can be converted into a large amount of energy. Thus, when two light atomic nuclei, such as those of deuterium and tritium, combine to form a heavier nucleus (in this case, helium), the total mass of the resulting particles is less than the sum of the initial masses. This 'missing' mass is converted into energy. Specifically, in the fusion process, part of the mass of the hydrogen isotopes is converted into kinetic energy, which is subsequently transformed into heat. The heat can then be converted into electrical energy via a steam turbine. The working fluid to be employed in the fusion generator is water in accordance with the basic Rankine cycle [10].

DT Fusion Parameters Applicable to the DCF Plasma

- **a.** Particle density and temperature: Desired particle density of about 10^{20} m^{-3} to 10^{31} m^{-3} and temperature of 10 KeV to 20 KeV.
- **b.** Application of Lawson Criterion.
- **c.** Triple nT_TE for D-T fusion in 10 – 20 KeV range. ($nT\tau E \geq 3 \times 10^{21}$keV s m^{-3})
- **d.** Physics Gain Factor Q > 5 and Engineering Gain Factor Q_e.

These parameters have been simulated using MATLAB and found to be in consonance with their applicability to the DCF studies.

Conversion of Gamma Count Rate to Gamma Dose Rate

Oftentimes, the measurement of ionizing radiation is expressed as a rate of counts per unit time, which is registered by a radiation monitoring instrument, for which counts per second (cps) is a commonly used quantity. Count rate measurements are associated with the detection of particles, such as alpha particles and beta particles. However, for gamma ray and X-ray dose measurements, a unit such as the sievert is used. The cps is the rate of detected events registered by the measuring instrument and not the rate of emission from the source of radiation. For radioactive decay measurements, it must not be confused with disintegrations per unit time (dpm), which represents the rate of atomic disintegration events at the source of the radiation [11].

The count rate of cps is generally accepted and a convenient practical rate measurement, and is a measure of the detection rate of ionization events per second. The cps is majorly used for measurements when higher count rates are encountered, such as in DT fusion reactions. Count rate does not universally equate to dose rate and there is no simple universal conversion factor. Any conversions are instrument-specific. While counts are the number of events detected, but dose rate relates to the amount of ionizing energy deposited in the radiation detector. The conversion calculation is dependent on the radiation energy levels, the type of radiation being detected, and the radiometric characteristics of the detector [11].

Thus, the Spectrum-based dose calculations [8] that give the dose at the detector location without regard to the type of gamma-ray source are accomplished by applying the GADRAS Detector Response Function (DRF), which defines full-energy (i.e., photopeak) efficiencies and Compton continua as a function of gamma-ray energy. These spectrum-based dose calculations are performed sequentially by first estimating the fluence associated with photopeaks, then obtaining the fluence for the residual continuum. Conversely, in Eq. (1), the photon fluence Φ can be related to the quantity of photons Np crossing a sphere of cross-sectional area dA [12],

$$\Phi = \frac{Np}{dA\ [photon\ cm^{-2}]} \qquad (1)$$

The flux density or fluence rate $\dot{\Phi}$ is time-bound, and it relates in Eq. (1) as shown in Eq. (2):

$$\dot{\Phi} = \frac{d\Phi}{dt\ [photons\ cm^{-2}\ s^{-1}]} \qquad (2)$$

In Eq. (3), the fluences are computed by dividing the peak areas by the absolute photopeak efficiencies; then the computed detector response for each gamma ray is stripped from the measured spectrum. The detector response that is applied for this calculation does not include scatter into the detector, but scatter out of the detector is included in the detector response. Therefore, the continuum feature associated with Compton scatter out of the detector is removed when the spectrum is stripped, whereas scattering into the detector is retained as fluence on the detector. The residual spectrum is fit by linear regression to determine the fluence in each energy group according to the following relationship:

$$Yi = \sum_{j=1}^{n} FjRi,j$$

where Yi is the number of counts in energy group i, Fj is the gamma-ray fluence in energy group j, and the detector response, Ri,j, gives the counts in energy group i in response to gamma-ray emission in energy group j. These calculations produce a series of fluence estimates for both discrete gamma rays and continuum groups. The fluences are then processed to compute the dose rate according to:

$$X = \sum FihE(i) \qquad (4)$$

This provides the total dose rate that is equal to the sum of the products of the gamma-ray leakages times the fluence-to-dose factors as shown in Eq. (4), where Fi is the fluence, and hE(i) is a fluence-to-dose factor, which is a function of energy. Note that the fluence rate is the number of photons per unit area per unit time as shown in (1). Additionally, the photon fluence ψ ($MeVcm^{-2}$) is associated with the amount of energy dE crossing a unit area dA, and also, photon fluence rate $\dot{\psi}$ ($MeVcm^{-2}$ s^{-1}) is associated with the photon fluence over a unit time [12].

Gamma Count Rate and DT Fusion Neutron Yield Estimation

In an experiment at the Joint European Torus (JET) to measure the deuterium–tritium reaction gamma-ray emission in magnetic confinement fusion plasmas, Giulia Marcer et al [13] observed that in a DT fusion nuclear reaction, deuterium and tritium generate a ^5He nucleus in its second excited state in Eq. (5), which predominantly decays from the resonance level to the ground state of a ^4He nucleus through the emission of the well-known 14.1 MeV neutron [13, 14].

$$D + T \rightarrow {}^4He\ (3.5\ MeV) + {}^1n\ (14.1\ MeV) \qquad (5)$$

Alternatively, ^5He can decay radiatively to its own ground state or to its first excited state. In the former case, a 16.7 MeV gamma-ray (γ0) is produced while, in the latter, a 12.5 MeV gamma-ray (γ1) is emitted before the nucleus de-excites non-radiatively to the ground state [13, 14]. The absolute measurement of these radiative branches' emission could be used as a second direct method to measure the fusion power.

Their work aimed to measure the total DT gamma-ray emission during JET DT discharges and prove that this absolute measurement can be used to infer the fusion yield. For each discharge, the core principle adopted to measure the total gamma-ray yield Y relied on the analysis of the detector pulse height spectrum (PHS) and the plasma emission profile based on the formula in Eq. (6)

$$YTA\mathcal{E} = Cf \ \rightarrow \ Y = \frac{Cf}{TA\mathcal{E}}$$

where:

- T is the transport factor, which takes into account both the non-uniform plasma volumetric emission and the gamma rays optical transport toward the detector. It was determined with Monte Carlo simulations (MCNP), semi-analytical codes and plasma emission profile information derived from the JET neutron camera,
- A is the gamma-ray transmission factor through collimators and attenuators, the most important of which is a neutron attenuator located in front of the detector to suppress the intense neutron background,
- ε is the detector gamma-ray detection efficiency, which was determined with a novel technique based on the specific detector employed for this purpose,
- C is the integrated number of counts in the PHS in an optimized energy range defined as the region of interest (RoI),

• f is the fraction of DT gamma-ray events in the RoI.

Equation (6) can further be modified into a simplified form as:

$$Y = \frac{C}{\mathcal{E} \text{ x BR}}$$

where:

Y = the neutron yield (neutrons/s)
C = the gamma count rate (counts/s)
$\mathcal{E}$
BR = gamma branching ratio

Since it is possible to determine the dose rate at a detector location based on the gamma spectra without knowing the activity of the source and the detector distance from the source, it is then equally possible to estimate the spectrum (count rate) from a measured dose rate. From the estimated count rate, we can then estimate the fusion neutron yield from a DT fusion reaction as in Eq. (7). This approach can very aptly be applied to experiments and studies of the DCF.

2.0 METHODOLOGY

The following two steps, based on basic health physics principles, provide the details of the mathematical relationships, derivations, and calculations to achieve a realistic estimate of the fusion neutron yield from a measured gamma dose rate in a DCF setup.

2.1 Convert Dose Rate to Radiation Energy Absorption and Counts

In this step, we convert the radiation dose rates (Sv/h) to energy absorption rate and estimate the count rates based on the average photon energy. We also need to use the physical definition that 1 Gray (Gy) = 1 Joule/kg. Thus, to convert energy to counts, the total Joules per second is divided by the average photon energy in Joules through the following 3 sub-steps. Thereafter, we need to convert the energy rate to electron-volts per second (eV/s) and then to Joules before estimating the counts per second. This assumes an average photon energy (e.g. 12.5 or 16.7 MeV gamma from a DT Fusion reaction). The counts calculation assumes all energy is deposited by single-photon interactions, providing an approximate rate. We also need to assume that the mass of the target/tissue in kg is mass (kg) = 1, while the Quality Factor for gamma or x-ray is 1 (for an alpha particle, it is 20).

a. **Sub-Step 1.1** Convert Dose Rate (Sv/h) to Absorbed Dose Rate (Gy/h) This sub-step considers that the dose in Sievert is given by:

Dose (in Sv) = Dose (in Gy) x Quality Factor (Q factor) *(8)*

where Q factor =1 i.e.

Dose(Sv) = Dose(Gy) * Q factor or

$$\text{Dose Rate (Gy/h)} = \frac{\text{Energy Rate }(\frac{J}{h})}{\text{Mass (kg)}} \tag{9}$$

since 1 Gy = 1 J/kg and mass (kg) =1, then,
DoseRate (Gy/h) = DoseRate (Svh) / Q factor; and
EnergyRate_Jh = DoseRate_Gy_h * mass_kg

b. Sub-Step 1.2 Calculate Approximate Count Rate
To convert Energy Rate to eV/s, we consider that 1 Joule = 6.242e18 eV.
Hence, converting hours to seconds, we obtain:

$$\text{Energy Rate (eV)} = \frac{\text{Energy Rate (J/h)}}{\text{3600 (for seconds) x mass (in kg)}} \tag{10}$$

$$\text{ie energyRate\_(eVs)} = \left(\frac{\text{energyRate (Jh)}}{3600}\right) * 6.242e18$$

c. Sub-Step 1.3 Estimate Counts per second. In this sub-step, we consider that:

$$\text{Counts} = \frac{\text{Total Energy}}{\text{Average Photon Energy}} \tag{11}$$

In other words,

$$\text{Count Rate (in cps)} = \frac{\text{Energy Rate (eVs)}}{\text{Average Energy (eV)}} \tag{12}$$

2.2 Determine the DT Fusion Neutron Yield from Estimated Gamma Yield

In this second step, we estimate the Deuterium-Tritium (DT) total fusion neutron yield (Y_{DT}) based on measured Gamma-ray counts ($C\gamma$), detector efficiency (ϵ), and the branching ratio ($BR\gamma/n$) between fusion gamma rays and neutrons.

a. Sub-Step 2.1 Input Parameter
We need to provide the average detector efficiency (percentage of gamma rays detected). Since we are using the HFS-10 Geiger-Mueller Nuclear Radiation Detector (with an efficiency between 17% and 25%), we can use an average efficiency of 0.21 (21%).

b. Sub-Step 2.2 Range of measured gamma-ray counts (e.g. 10^3 to 10^7) We also need to specify the range of the measured gamma-ray counts and applicable branching ratios BR_0 and BR_1 to test using a range around the commonly found 2.4e-5 and 4.2e-5 values, respectively, for DT Fusion gammas. The values of the DT fusion gamma branching ratios found in the literature are as varied as the literature itself. Hence, for more realistic values [15], we will use BR_0 = 1.13e-5 and BR_1 = 1.23e-5.

c. Sub-Step 2.3 Calculate Fusion Neutron Yield

To determine the estimated neutron yield, we can apply the relationship for each branch:

$$\text{Total Neutron Yield Y} = \frac{\text{Counts}}{\text{Detector Efficiency x Branching Ratio}} \quad (13)$$

$$\text{ie, Fusion Yield} = \frac{\text{Gamma\_counts}}{\text{efficiency} * \text{br}}$$

3.0 RESULTS

The design stage graphical user interface (GUI) is shown in "Fig 1". It has three main frames for input parameters, output values, and graphical displays of results. The frame for the input parameters includes measured dose rate, detector efficiency, gamma energy 1, gamma energy 2, branching ratio 1, and branching ratio 2. This frame also includes buttons for the loading of input default values, resetting of both input parameters, output values and graphical displays as well as for the calculation and plotting of graphs. The frame for the output values includes measured dose rate, energy absorption rate, approximate count rate 1, approximate count rate 2, total gamma count rate, approximate neutron yields 1, approximate neutron yields 2 and total fusion neutron yield. During the run phase, the main graphical display shows the relationships between the total neutron yield and the total gamma counts for both the two gamma branching ratios as well as the total gamma counts. The minor graphical display shows only the approximate gamma counts for the two gamma-based branching ratios.

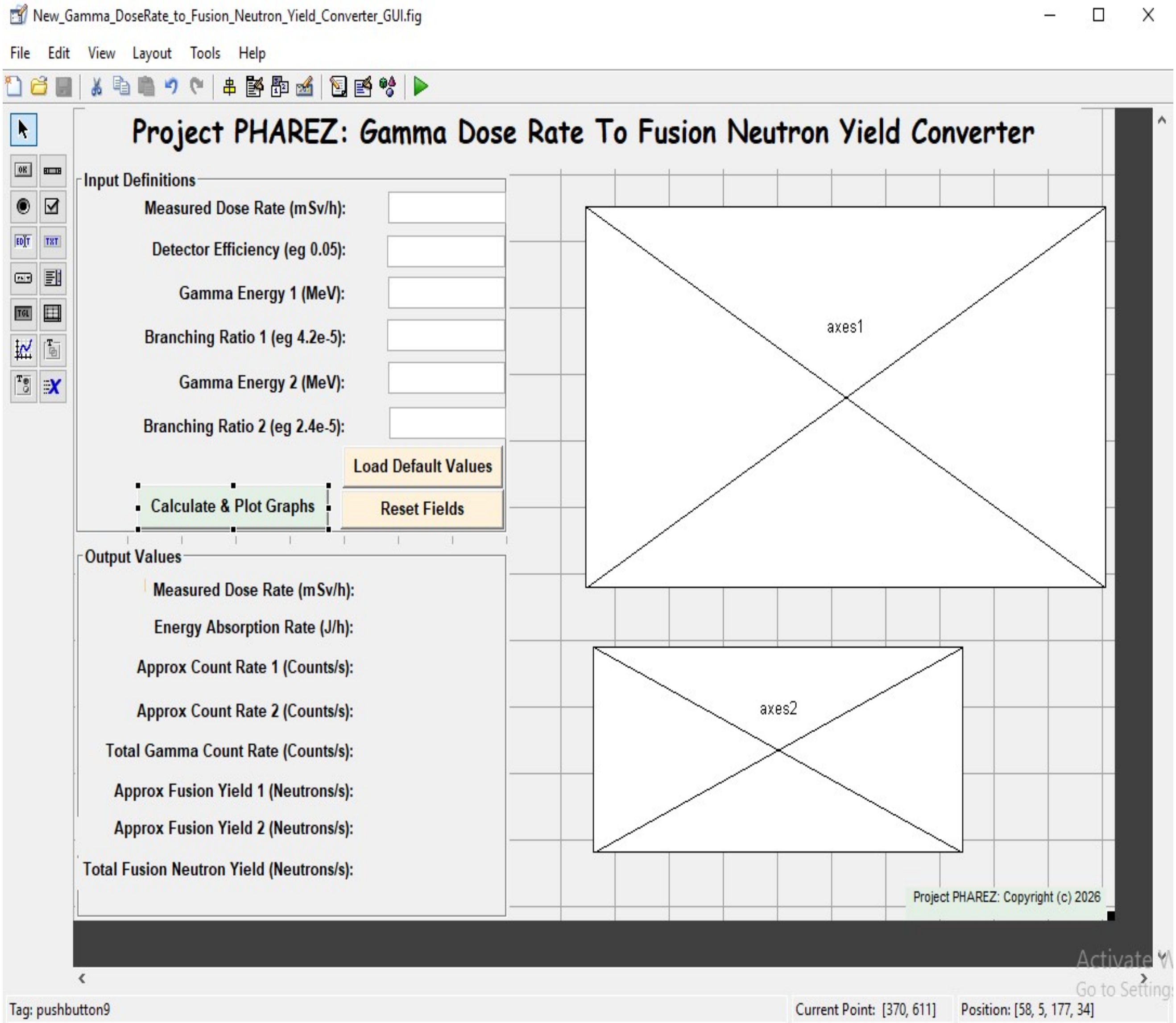

Fig 1: Design Stage Graphical User Interface

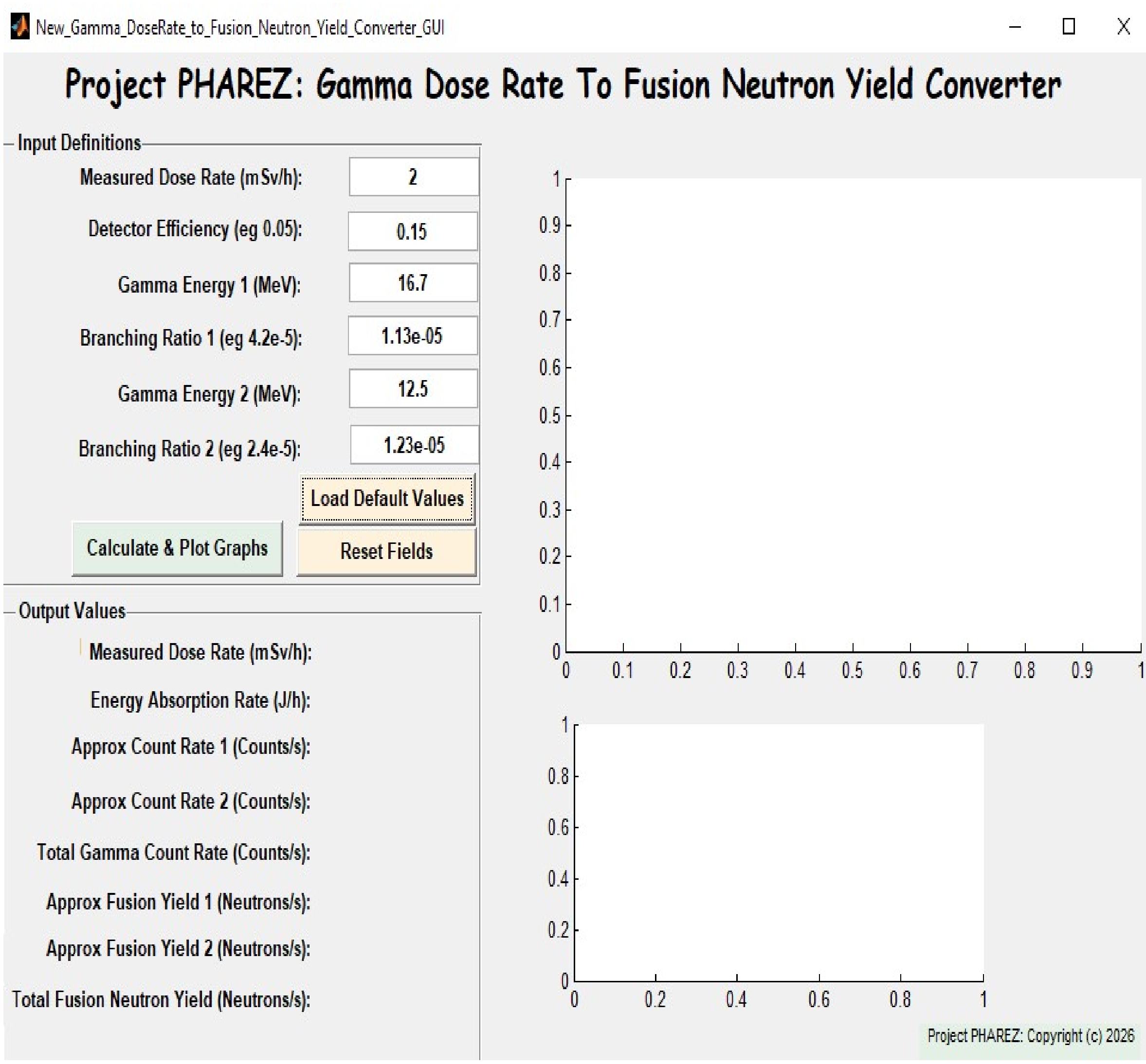

Fig 2: Run Phase Graphical User Interface 1

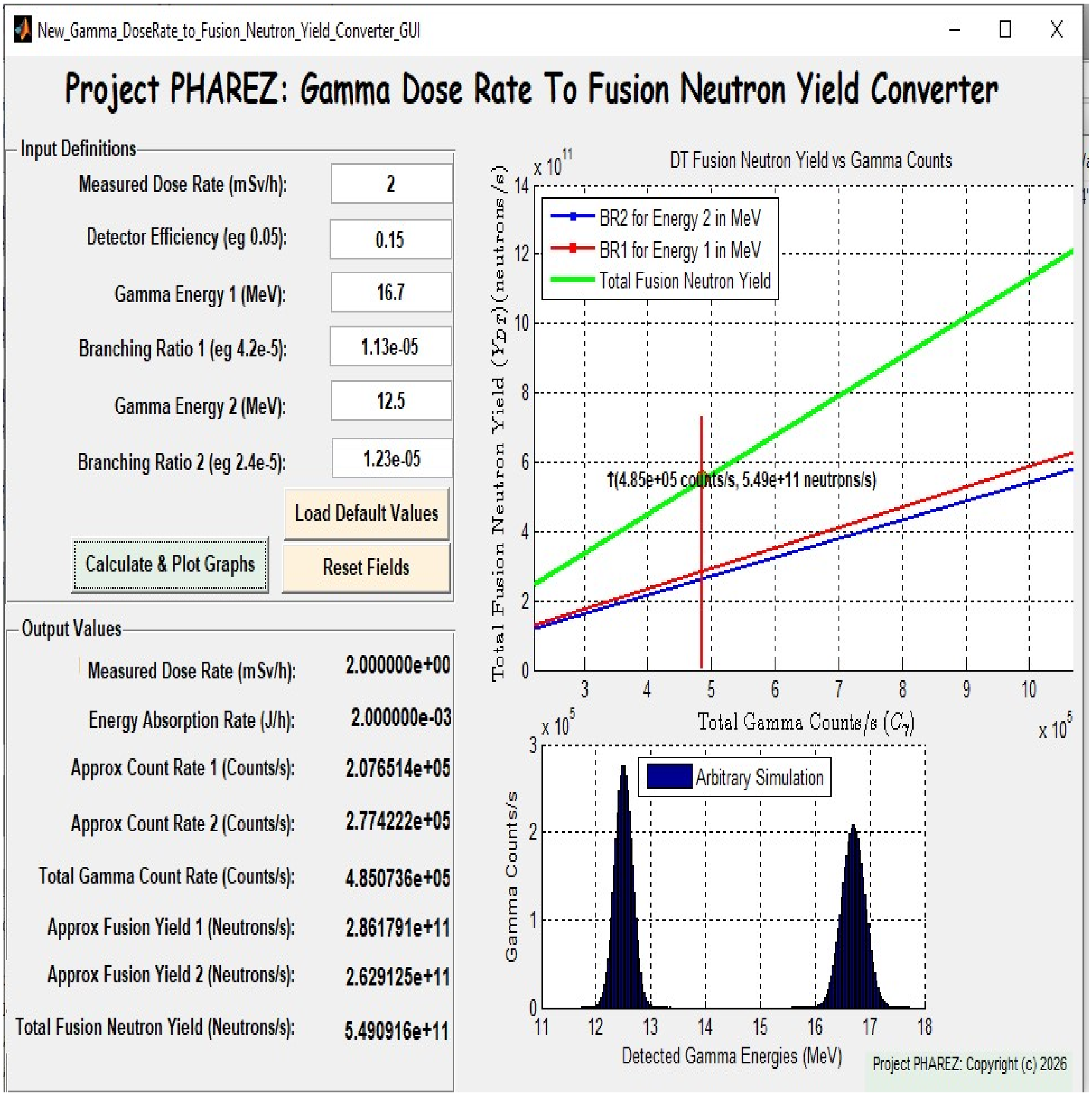

Fig 3: Run Phase Graphical User Interface 2

In the run phase, when clicking on the ‘Load Default Values’ button, the default values fields are populated as shown in “Fig 2”. These fields can manually be populated as needed. Clicking on the ‘Reset Fields’ button will clear all the displays in all the fields as well as the graphical displays. By clicking on the ‘Calculate & Plot Graphs’ button will display the output values and plot the relevant graphs. It is to be noted that the computations for the plotting of the graphs initially take some time. As such, the graphs may not be displayed as fast as the numerical displays. The numerical and graphical displays are as shown in “Fig 3”.

4.0 CONCLUSION

As a first step towards the design and implementation of a gamma diagnostic system for our novel DCF generator system, we have designed and implemented a cheaper approach to estimate the DT Fusion neutron yield from a measured gamma dose rate from the fusion reaction. The estimation is based on basic health physics principles and not on the finesse of the relationships of gamma sources in a DT fusion environment, especially in our novel DCF setup. As we improve on our studies, more efficient relationships will be developed and accordingly implemented following this novel approach.

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