γ-ray spectrometry for diagnosing high-repetition-rate Laser Direct-Drive Inertial-Fusion-Energy implosions

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Executive Summary

Power production from Laser Direct-Drive Inertial Fusion Energy (LDD-IFE) is not far from realization now based on recent breakthroughs in Inertial Confinement Fusion (ICF) research, which builds upon decades of research of the laser direct-drive concept, and reasonable extensions of existing laser, diagnostic, and target technologies. This white paper presents a Gamma-RAy SPectrometer (GRASP), based on Compton scattering, for diagnosing high-repetition-rate IFE implosions. The design philosophy behind this system is that only power output and thus fusion yield per shot need to be diagnosed. The detector backend must also be able to handle a repetition rates up to 10 Hz and be well-shielded for adequate signal-to-background and long-life span. This means it has to be positioned behind the reaction-chamber shield wall at a relatively large distance and be fully enclosed by shielding. At this distance, γ-rays are more ideal to diagnose than fusion neutrons. In this system, only the beryllium-conversion foil will be exposed to the direct flux of incoming γ's (and neutrons). The spectrometer design consists of three small clam-shell-like dipoles with small quadrupoles positioned in front and behind the dipoles for correction of higher-order aberrations. Permanent magnets will be used, and the central B-field in the different dipoles will vary from 0.1 to 0.4 T to cover the full energy range 0.2 – 20 MeV. Simulations were conducted to evaluate the diagnostic performance for a 100 MJ IFE implosion. From the measured spectrum of the Compton-scattered electrons, the absolute spectrum of the incoming γ-rays will be determined, from which fusion yield and possibly fuel and ablator areal-density will be inferred.

1.   Introduction

Since the dawn of the Inertial Confinement Fusion (ICF) research, numerous studies of Inertial Fusion energy (IFE) as a viable energy source have been conducted [1]. Most of these studies focused on the driver, target manufacturing and target designs for high-repetition rates, reaction-chamber designs, tritium handling, energy balance and economics. With the recent success at the National Ignition Facility (NIF) when implosion experiments produced 1.35 MJ of fusion energy, a renewed interest for IFE has occurred. To the best of our knowledge, none of these earlier IFE studies looked at diagnostics required for an IFE facility, indicating ample opportunities for diagnostics-design work relevant to IFE applications. To that end, this white paper presents a Gamma-RAy SPectrometer (GRASP), based on Compton scattering, for diagnosing high-repetition-rate IFE implosions. The design philosophy behind this system is that power output and thus fusion yield per shot are the primary observables to be diagnosed. Perhaps the information about the fusion-source location, and fuel and ablator-areal density is relevant for an IFE facility and should be also diagnosed. In addition, the detector backend must be able to handle a repetition rate up to 10 Hz and be well-shielded for adequate signal-to-background and long-life span. This means that the spectrometer has to be positioned behind the reaction-chamber shield wall at a relatively large distance and be fully enclosed by shielding. At this distance, the prompt γ-rays arrive first at the detector during a short time window when the background is at minimum and are therefore more ideal to diagnose than fusion neutrons. This is the primary motivation for the implementation of GRASP.

2.   The GRASP system for IFE
2.1   The IFE γ-ray spectrum

The spectrum of γ-rays from an IFE implosion is anticipated to originate from several sources and be very broad. FIG. 1 illustrates a simulated γ-ray spectrum from a typical direct-drive implosion [2]. In addition to the γ-rays from DT-fusion reactions, which has a broad spectrum, 4.44-MeV γ-rays from $^{12}C(n,n'\gamma)$ reactions, 15.58-MeV γ-rays from $^{2}H(n,\gamma)^{3}H$ reactions, and the 14.18-MeV and 17.87-MeV γ-rays from $^{12}C(n,\gamma)^{13}C$ reactions can be used to diagnose an IFE implosion [3].
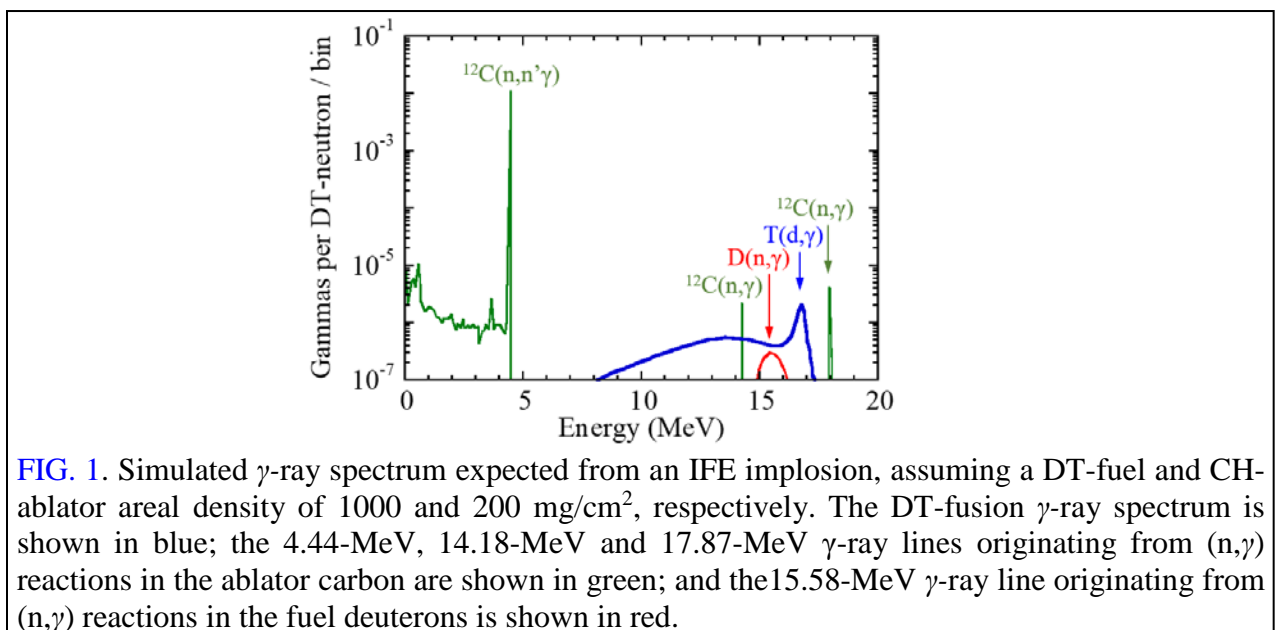

FIG. 1. Simulated γ-ray spectrum expected from an IFE implosion, assuming a DT-fuel and CH-ablator areal density of 1000 and 200 mg/cm², respectively. The DT-fusion γ-ray spectrum is shown in blue; the 4.44-MeV, 14.18-MeV and 17.87-MeV γ-ray lines originating from (n,γ) reactions in the ablator carbon are shown in green; and the 15.58-MeV γ-ray line originating from (n,γ) reactions in the fuel deuterons is shown in red.

2.1 Conceptual GRASP design and simulated performance

2.1.1 Design guidelines

The entire spectrum has never been validated experimentally, which is one of the motivations for why the diagnostic must provide high spectral resolution to be able to discern DT-fusion γ's from other γ's shown in FIG. 1. Given that the γ-ray yield per produced neutron is low [4] and that the spectrum is anticipated to be broad, it is important to develop a broad-band GRASP system with both adequate efficiency and energy resolution to be able to diagnose the different components in the γ-ray spectrum and determine the absolute fusion yield from each implosion at an IFE facility. When optimizing the GRASP deign for IFE applications, there are several guiding principles that should be considered:

1. Maximize efficiency for a given energy resolution by selecting close-to forward-scattered Compton electrons (as described by Klein-Nishina expression for the differential cross section [5]).
2. Maximize the probability for Compton scattering relative to pair production to generate an electron spectrum similar to the spectrum of the incident γ-rays. As pair production scales with Z^2, this is done by selecting a conversion foil with low atomic number ($Z < 6$).
3. Maximize efficiency by using largest possible solid angles subtended by the conversion foil and magnet aperture, without seriously degrading the energy resolution. Here, the foil and aperture distances and areas, dictated by the IFE facility design, play a central role.
4. Maximize efficiency by selecting thickest possible foil while maintaining an adequate energy resolution.
5. Maximize S/B by using a magnet that bends the scattered electrons to a shielded location where they are detected by a smallest-possible detector.
6. Maximize the ability of the magnet system to focus electrons from an extended source (the foil).
7. Maximize the radiation hardness of the detector.
8. Minimize the impact of the detector spatial resolution on the energy resolution of the system.
9. Minimize the recovery time of the detector to be fully operational for the subsequent shot.

In the process of maximizing the spectrometer efficiency, it is essential to maintain an energy resolution to an adequate level. As these parameters have different sensitivities, finding an optimal trade-off between them is essential.

2.1.2 Conceptual design

As already mentioned, the GRASP system will be based on Compton scattering in which incoming γ-rays scatter off electrons in a conversion foil made of beryllium. A compact permanent-magnet system will be used for momentum dispersion and focusing of the emitted Compton electrons onto a focal plane at which they will be detected by a spatially-resolving detector.

The current idea is to use a radiation-hardened CVD microstrip detector that provides the necessary temporal resolution for repetition-rate applications and spatial resolution (equivalent to energy resolution) along the focal plane of the spectrometer. As CVD diamond material is an extremely radiation hard material and well suited for in the high-repetition rate and high radiation environments. The width of each strip sets the energy bin of the recorded spectrum.

The diagnostic will be positioned behind the reaction-chamber shield wall at a relatively large distance, and the detector will be fully enclosed by shielding and displaced off the direct diagnostic line of sight. Only the beryllium-conversion foil be exposed to the direct flux of incoming γ's (and neutrons). From the measured spectrum of the Compton-scattered electrons, the absolute spectrum of the incoming γ-rays will be determined. One of the great advantages of this type of system is that it can be accurately characterized from first principles.

The conceptual design of the GRASP system is shown in FIGS. 2a and b. This compact system will cover an energy range of 0.2 – 20 MeV to cover most of the key components of the γ-ray spectrum shown in FIG. 1. The heart of the system is the set of three simple clam-shell-like dipoles, two of which are shown in the figure. The third dipole not shown will be positioned off the figure plane to cover the energies below 4 MeV. Small quadrupoles will be used in front and behind the dipoles for correction of higher-order aberrations. Permanent magnets will be used, and the central B-field in the different dipoles will vary from 0.1 to 0.4 T to cover the full energy range. The charged-particle code COSY [6] was used to design the electron-optics of the GRASP magnet system.
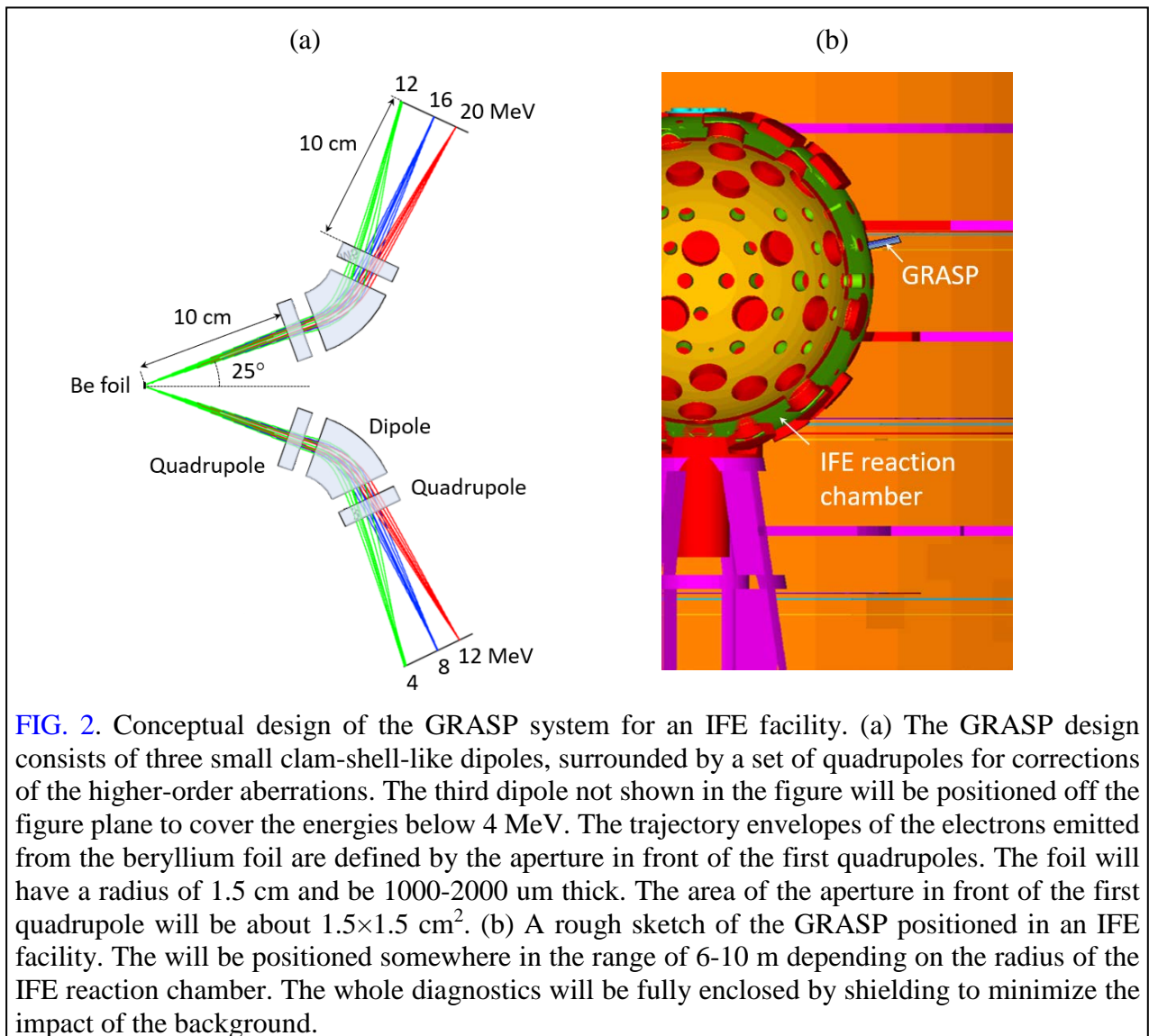

FIG. 2. Conceptual design of the GRASP system for an IFE facility. (a) The GRASP design consists of three small clam-shell-like dipoles, surrounded by a set of quadrupoles for corrections of the higher-order aberrations. The third dipole not shown in the figure will be positioned off the figure plane to cover the energies below 4 MeV. The trajectory envelopes of the electrons emitted from the beryllium foil are defined by the aperture in front of the first quadrupoles. The foil will have a radius of 1.5 cm and be 1000-2000 um thick. The area of the aperture in front of the first quadrupole will be about 1.5×1.5 cm^2. (b) A rough sketch of the GRASP positioned in an IFE facility. The will be positioned somewhere in the range of 6-10 m depending on the radius of the IFE reaction chamber. The whole diagnostics will be fully enclosed by shielding to minimize the impact of the background.

2.1.3 Simulated performance

A Monte-Carlo code was developed and used to simulate the performance of the GRASP design and the results are shown in FIGS. 3a and b. The Compton-electron spectra were generated from a DT gas-filled implosion that produced 3×10^{19} neutrons (~100 MJ) and a DT-fuel and CH-ablator areal density of 1000 and 200 mg/cm^2, when the GRASP was positioned 6 m and 10 m away from the implosion. The GRASP configurations used in these simulations are illustrated in TABLE 1 together with some performance numbers. In addition, these spectra were generated under the assumption that the detector is substantially shielded and background has an insignificant impact on the data. From this type of data, fusion yield, fuel and CH ablator areal density can be inferred for each IFE implosion.
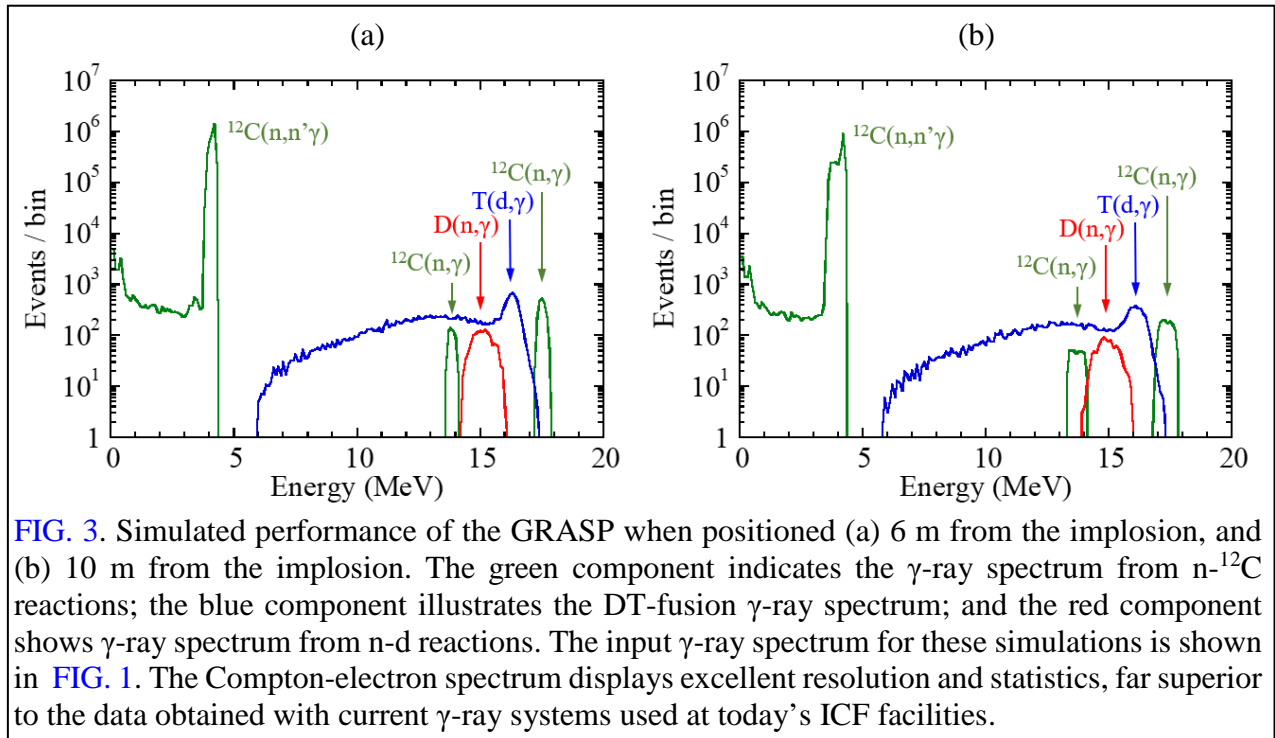

FIG. 3. Simulated performance of the GRASP when positioned (a) 6 m from the implosion, and (b) 10 m from the implosion. The green component indicates the γ-ray spectrum from n-^{12}C reactions; the blue component illustrates the DT-fusion γ-ray spectrum; and the red component shows γ-ray spectrum from n-d reactions. The input γ-ray spectrum for these simulations is shown in FIG. 1. The Compton-electron spectrum displays excellent resolution and statistics, far superior to the data obtained with current γ-ray systems used at today's ICF facilities.

TABLE 1. Configurations and performance of the GRASP system

	FIG. 3a	FIG. 3b
Foil distance (m)	6.0	10.0
Foil thickness (μm)	1000	2000
Foil radius (cm)	1.5	1.5
Aperture area (cm^2)	2.25	2.25
Efficiency	2.6×10^{-11}	1.9×10^{-11}
Resolution (keV)	460	870

3. References

[1] National Research Council 2013. An Assessment of the Prospects for Inertial Fusion Energy. Washington, DC: The National Academies Press. https://doi.org/10.17226/18289.

[2] Y. Kim, H. W. Herrmann, T. J. Hilsabeck, K. Moy, W. Stoeffl, J. M. Mack, C. S. Young, W. Wu, D. B. Barlow, J. B. Schillig, J. R. Sims, Jr., F. E. Lopez, D. Mares, J. A. Oertel, and A. C. Hayes-Sterbenz, "Gamma-to-electron magnetic spectrometer (GEMS): An energy-resolved γ-ray diagnostic for the National Ignition Facility", Rev. Sci. Instrum. 83, 10D311 (2012).

[3] N. M. Hoffman, D. C. Wilson, H. W. Herrmann, and C. S. Young, "Using gamma-ray emission to measure areal density of inertial confinement fusion capsules", Rev. Sci. Instrum. 81, 10D332 (2010).

[4] Y. Kim, J. M. Mack, H. W. Herrmann, C. S. Young, G. M. Hale, S. Caldwell, N. M. Hoffman, S. C. Evans, T. J. Sedillo, A. McEvoy, J. Langenbrunner, H. H. Hsu, M. A. Huff, S. Batha, C. J. Horsfield, M. S. Rubery, W. J. Garbett, W. Stoeffl, E. Grafil, L. Bernstein, J. A. Church, D. B. Sayre, M. J. Rosenberg, C. Waugh, H. G. Rinderknecht, M. Gatu Johnson, A. B. Zylstra, J. A. Frenje, D. T. Casey, R. D. Petrasso, E. Kirk Miller, V. Yu Glebov, C. Stoeckl, and T. C. Sangster, "D-T gamma-to-neutron branching ratio determined from inertial confinement fusion plasmas", Phys. Plasmas 19, 056313 (2012).

[5] Klein O., Nishina Y., "The scattering of light by free electrons according to Dirac's new relativistic dynamics", Nature 122, 398 (1928).

[6] K. Makino, M. Berz, "COSY INFINITY version 8", Nucl. Instr. and Meth. A 427 (1999) 338; M. Berz, COSY Infinity, http://www.bt.pa.msu.edu/index_files/cosy.htm.