LLNL-PROC-680808

Nuclear Diagnostics at the National Ignition Facility, 2013-2015

C. B. Yeamans, W. S. Cassata, J. A. Church, D. N. Fittinghoff, N. Gharibyan, R. Hatarik, D. B. Sayre, R. M. Bionta, D. L. Bleuel, J. A. Caggiano, C. J. Cerjan, M. J. Eckart, P. M. Grant, G. P. Grim, E. P. Hartouni, A. J. Mackinnon, K. J. Moody, M. J. Moran, T. W. Phillips, H. G. Rinderknecht, D. H. G. Schneider, S. M. Sepke, D. A. Shaughnessy, W. Stoeffl, C. A. Velsko, M. Gatu Johnson, H. W. Sio, J. A. Frenje, R. D. Petrasso, G. W. Copper, E. R. Edwards, S. A. Faye, C. J. Forrest, V. Yu Glebov, J. P. Knauer, W. Herrmann, F. E. Merrill, P. Volegov, J. D. Kilkenny

January 12, 2016

IFSA
Seattle, WA, United States
September 20, 2015 through September 25, 2015

Nuclear Diagnostics at the National Ignition Facility, 2013-2015

C B Yeamans[1], W S Cassata[1], J A Church[1], D N Fittinghoff[1], M Gatu Johnson[4], N Gharibyan[1], R Határik[1], D B Sayre[1], H W Sio[4], R M Bionta[1], D L Bleuel[1], J A Caggiano[1], C J Cerjan[1], G W Copper[6], M J Eckart[1], E R Edwards[5], S A Faye[5], C J Forrest[7], J A Frenje[4], V Yu Glebov[7], P M Grant[1], G P Grim[1], E P Hartouni[1], H W Herrmann[3], J D Kilkenny[2], J P Knauer[7], A J Mackinnon[1], F E Merrill[3], K J Moody[1], M J Moran[1], R D Petrasso[4], T W Phillips[1], H G Rinderknecht[1], D H G Schneider[1], S M Sepke[1], D A Shaughnessy[1], W Stoeffl[1], C A Velsko[1], P Volegov[3]

[1] Lawrence Livermore National Laboratory, Livermore, California, USA
[2] General Atomics, San Diego, California, USA
[3] Los Alamos National Laboratory, Los Alamos, New Mexico, USA
[4] Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[5] University of California, Berkeley, Berkeley, California, USA
[6] University of New Mexico, Albuquerque, New Mexico, USA
[7] University of Rochester, Laboratory for Laser Energetics,Rochester, New York,USA

Email: yeamans1@llnl.gov

Abstract. The National Ignition Facility (NIF) relies on a suite of nuclear diagnostics to measure the neutronic output of experiments. Neutron time-of-flight (NTOF) and neutron activation diagnostics (NAD) provide performance metrics of absolute neutron yield and neutron spectral content: spectral width and non-thermal content, from which implosion physical quantities of temperature and scattering mass are inferred. Spatially-distributed flange-mounted NADs (FNAD) measure, with nearly identical systematic uncertainties, primary DT neutron emission to infer a whole-sky neutron field. An automated FNAD system is being developed. A magnetic recoil spectrometer (MRS) shares few systematics with comparable NTOF and NAD devices, and as such is deployed for independent measurement of the primary neutronic quantities. The gas-Cherenkov Gamma Reaction History (GRH) instrument records four energy channels of time-resolved gamma emission to measure nuclear bang time and burn width, as well as to infer carbon areal density in experiments utilizing plastic or diamond capsules. A neutron imaging system (NIS) takes two images of the neutron source, typically gated to create coregistered 13-15 MeV primary and 6-12 MeV downscattered images. The radiochemical analysis of gaseous samples (RAGS) instrument pumps target chamber gas to a chemical reaction and fractionation system configured with gamma counters, allowing measurement of radionuclides with half-lives as short as 8 seconds. Solid radiochemistry collectors (SRC) with backing NAD foils collect target debris, where activated materials from the target assembly are used as indicators of neutron spectrum content, and also serve as the primary diagnostic for nuclear forensic science experiments. Particle time-of-flight (PTOF) measures compression-bang time using DT- or DD-neutrons, as well as shock bang-time using D^3He-protons for implosions with lower x-ray background. In concert, these diagnostics serve to measure the basic and advanced quantities required to understand NIF experimental results.

1. NIF Nuclear Diagnostics

The National Ignition Facility (NIF) relies on a suite of nuclear diagnostics to measure the neutronic output of experiments in inertial confinement fusion, high energy density physics, and fundamental sciences. These instruments are essential to understanding complex stagnation physics. The NIF Conceptual Design Review provided the framework for laser diagnostics [1] and target diagnostics [2], including substantial conceptual design of nuclear diagnostics [3], well in advance of anticipated full-scale fusion experiments. After commissioning, the NIF Execution Plan allowed for refinement of design [4],[5]. Subsequent full-scale ignition experiments [6] utilized these and became the physics and experiential basis [7] for the development described herein. New simulations have better diagnostic output capability [8], so better relation can be made between measurements and underlying physical quantities. Substantial evolution in capability is required to understand high convergence implosions: plasma conditions, signatures of alpha heating, and artifacts of fundamentally-3D effects.

1.1. Neutron Time-of-Flight (NTOF)

Neutron time-of-flight (NTOF) measures the capsule neutron spectrum from three unique directions, with a fourth under construction [9], by amplifying the light output of a bibenzyl scintillator [10]. The physical quantities of plasma temperature and scattering mass are inferred from the measured neutron spectrum: width and non-thermal content. To cover the widest range of yields and neutron energies, both precision collimated [11] and robust radiation-hard designs [12] were implemented [13]. Precision and yield ranges are being substantially improved [14]. Improved analysis capabilities include absolute timing, advanced spectrum fitting [15], and spectral moment analysis [16].

1.2. Neutron Activation Diagnostics (NADs)

Neutron activation diagnostics (NADs) provide the basic performance metric of absolute neutron yield [17],[18],[19]. Additionally, spatially-distributed flange-mounted NADs (FNADs) measure, with nearly identical systematic uncertainties, primary DT neutron emission to infer a whole-sky neutron field [20]. Real-time NADs, based on a lanthanum bromide scintillator and compact gamma spectrometer installed in the target bay, are being developed to provide immediate postshot readout of yield in a modular and expandable integrated system design [21]. This system will have additional physics capability to measure multiple DT neutron reactions [22] and other neutron source terms [23].

1.3. Magnetic Recoil Spectrometer (MRS)

A magnetic recoil spectrometer (MRS) shares few systematics with NTOF and NADs, and as such is deployed as an independent measurement of the primary neutronic quantities [24],[25]. A deuterated plastic foil converts neutrons to deuterons, and subsequent magnetic fields bend particles to CR39 plastic detectors. Particle tracks are developed by etching and are analyzed for number and size to unfold the source neutron spectrum. The MRS measures fuel and ablator areal density (ρR) of the implosion [26], as well as detecting signatures of non-3D effects, such as bulk neutron velocity [27].

1.4. Gamma Reaction History (GRH)

The gas-Cherenkov Gamma Reaction History (GRH) instrument [28],[29],[30] records four energy channels of time-resolved gamma emission to measure nuclear bang time and burn width [31], as well as infer carbon areal density [32] in experiments utilizing plastic or diamond capsules. GRH utilizes Cherenkov radiation emission from Compton-converted electrons to detect high-energy gamma rays of nuclear origin. Forward-fit of the signal [33],[34] provides burn-averaged observables, including total DT fusion yield [35], total ρR, ablator ρR, and fuel ρR [36],[37]. A Mach-Zehnder recording system [38] meets the need for measurement of ultra-fast optical pulses [39] over large physical areas [40] necessitated by the NIF physical expanse and complicated target bay geometry. A new instrument with lowest-energy threshold at 1.8 MeV and high sensitivity, currently known as Super GCD (or GCD-3 at OMEGA), is being developed for use at OMEGA and NIF [41]. The Gamma-to-Electron Magnetic Spectrometer (GEMS) [42],[43] is designed to measure prompt γ-ray spectra during high-yield deuterium-tritium implosions when implemented [44], and will be capable of detecting the diagnostic signatures of alpha heating [45].

1.5. Neutron Imaging System (NIS) and Coregistered Neutron and X-ray Imaging (CNXI)
NIS takes two highly-resolved images of the neutron source, typically gated to create coregistered primary (13-15 MeV) and downscattered (6-12 MeV) images [46],[47] after single-image reconstruction [48]. A second neutron imaging system is being built to enable multiple views and eventually full 3D neutron source reconstruction [49]. CNXI measures neutrons and x rays on a common line of sight using an image plate stack with interstitial n-p converter foils [50].

1.6. Radiochemical Analysis of Gaseous Samples (RAGS)
RAGS pumps target chamber gas to a chemical reaction and fractionation system designed with pulse-counting gamma spectrometers, allowing measurement of radionuclides with half-lives as short as 8 seconds [51],[52]. Operation of the system takes place automatically after a NIF shot to collect, concentrate, and analyze noble gas samples for radioactive isotopic composition with efficiencies of 80-100%. Additionally, stable samples may be retrieved for mass spectroscopy. Measurements of fission product yields support nuclear forensic science experiments [53]. Capsule tracer studies may also be performed, probing ablator/fuel mix [54] and plasma stopping power [55].

1.7. Solid Radiochemistry Collectors (SRC)
SRCs with backing NAD monitor foils collect target debris [56]. Activated gold from the hohlraum is collected, chemically leached from collectors [57], and the ratio of ^{198}Au (low-energy capture) to ^{196}Au (high-energy n,2n) is used as a spatially-averaged measure of fuel and ablator ρR [58],[59]. They also serve as the primary diagnostic for nuclear forensic science experiments [60],[61]. Additionally, the backing NADs are used as a diagnostic of neutrons above the primary DT neutron energy created by reactions of upscattered D and T in flight [62],[63].

1.8. Particle Time-of-Flight (PTOF)
PTOF uses a CVD diamond detector to measure the compression bang time using DT- or DD-neutrons [64],[65]. It also measures shock bang time using D^{3}He-protons [66] and ρR evolution [67] in implosions with lower x-ray background. A shielded detector using a bending magnet allows interrogation of more meaningful surrogate reactions [68].

References

[1] Kilkenny J D *et al.* 1995 *Rev. Sci. Instrum.* **66** 288
[2] Leeper R J *et al.* 1997 *Rev. Sci. Instrum.* **68** 868
[3] Moran M J and Hall J 1997 *Rev. Sci. Instrum.* **68** 521
[4] Murphy T J *et al.* 2001 *Rev. Sci. Instrum.* **72** 773
[5] Glebov V Yu *et al.* 2006 *Rev. Sci. Instrum.* **77** 10E715
[6] Lindl J D *et al.* 2014 *Phys. Plasmas* **21** 129902
[7] Kilkenny J D *et al. Fus. Sci. Tech.* accepted
[8] Clark D S *et al.* 2015 *Phys. Plasmas* **22** 022703
[9] Caggiano J A *et al.* these proceedings
[10] Határik R *et al.* 2012 *Rev. Sci. Instrum.* **83** 10D911
[11] Glebov V Yu *et al.* 2010 *Rev. Sci. Instrum.* **81** 10D325
[12] Moran M J 2012 *Rev. Sci. Instrum.* **83** 10D312
[13] Murphy T J *et al.* 2001 *Rev. Sci. Instrum.* **72** 850
[14] Grim G P *et al.* these proceedings
[15] Határik R *et al.* these proceedings
[16] Munro D H *J. Nucl. Fus.* accepted
[17] Barnes C W, Murphy T J and Oertel J A 2001 *Rev. Sci. Instrum.* **72** 818

[18] Bleuel D L *et al.* 2012 *Rev. Sci. Instrum.* **83** 10303
[19] Cooper G W *et al.* 2012 *Rev. Sci. Instrum.* **83** 10D918
[20] Bleuel D L *et al.* 2013 *EPJ Web of Conferences* **59** 13015
[21] Jedlovec D R, Edwards E R, Carrera J A and Yeamans C B 2015 *Proc. SPIE* **9591** 95910H
[22] Yeamans C B, Bleuel D L and Bernstein L A 2012 *Rev. Sci. Instrum.* **83** 10D315
[23] Edwards E R, Jedlovec D R, Carrera J A and Yeamans C B these proceedings
[24] Frenje J A *et al.* 2010 *Phys. Plasmas* **17** 056311
[25] Casey D T *et al.* 2013 *Rev. Sci. Instrum.* **84** 043506
[26] Gatu Johnson M *et al.* 2014 *Rev. Sci. Instrum.* **85**, 11E104
[27] Gatu Johnson M *et al.* 2013 *Phys. Plasmas* **20** 042707
[28] Moran M J 1999 *Rev. Sci. Instrum.* **70** 1226
[29] Malone R M *et al.* 2008 *Rev. Sci. Instrum.* **79** 10E532
[30] Hoffman N M *et al.* 2010 *Rev. Sci. Instrum.* **81** 10D332
[31] Herrmann H W *et al.* 2010 *Rev. Sci. Instrum.* **81** 10D333
[32] Hoffman N M *et al.* 2013 *Phys. Plasmas* **20** 042705
[33] Labaria G R *et al.* 2013 *Proc. SPIE* **8602** 86020C
[34] Sayre D B *et al.* 2012 *Rev. Sci. Instrum.* **83** 10D905
[35] Kim Y *et al.* 2012 *Phys. Plasmas* **19** 056313
[36] Hoffman N M *et al.* 2013 *EPJ Web of Conferences* **59** 13019
[37] Cerjan C *et al.* 2015 *Phys. Plasmas* **22** 032710
[38] Miller E K *et al.* 2012 *Rev. Sci. Instrum.* **83** 10D719
[39] Milnes J S *et al.* 2012 *Rev. Sci. Instrum.* **83** 10D301
[40] Milnes J S, Horsfield C J, Conneely T M and Howorth J 2014 *Rev. Sci. Instrum.* **85** 11E601
[41] Herrmann H W *et al.* 2014 *Rev. Sci. Instrum.* **85** 11E124
[42] Kim Y *et al.* 2012 *Rev. Sci. Instrum.* **83** 10D311
[43] Kim Y *et al.* 2014 *Rev. Sci. Instrum.* **85** 11E122
[44] Hermann H W *et al.* these proceedings
[45] Church J A *et al.* these proceedings
[46] Sweezy J E *et al.* 2006 *Rev. Sci. Instrum.* 77 10E722
[47] Merrill F E *et al.* 2012 *Rev. Sci. Instrum.* **83** 10D317
[48] Volegov P *et al.* 2014 *Rev. Sci. Instrum.* **85** 023508
[49] Fittinghoff D N *et al.* 2015 *Proc. SPIE* **9591** 95910E
[50] Merrill F E *et al.* 2014 *Rev. Sci. Instrum.* **85** 11E614
[51] Stoyer M A *et al.* 2012 *Rev. Sci. Instrum.* **83** 023505
[52] Shaughnessy D A *et al.* 2012 *Rev. Sci. Instrum.* **83** 10D917
[53] Cassata W S *et al. J. Radioanal. Nucl. Chem.* accepted
[54] Colvin J, Cerjan C, Hoffman R, Stoyer M and Amendt P 2008 *Phys. Plasmas* **15** 102704
[55] Hayes A C *et al.* these proceedings
[56] Gostic J M *et al.* 2012 *Rev. Sci. Instrum.* **83** 10D904
[57] Grant P M *et al.* 2015 *J. Radioanal. Nucl. Chem.*, v. **303**, 1851
[58] Shaughnessy D A *et al.* 2014 *Rev. Sci. Instrum.* **85** 063508
[59] Hagmann *et al.* 2015 *Rev. Sci. Instrum.* **86** 076105
[60] Gharibyan N et al. 2015 *J. Radioanal. Nucl. Chem.* **303** 1335
[61] Shaughnessy D A *et al.* these proceedings
[62] Grim G P *et al.* 2014 *Proc. SPIE* **9211** 921108
[63] Hayes A C *et al.* 2015 *Phys. Plasmas* **22** 082703
[64] Rinderknecht H G *et al.* 2012 *Rev. Sci. Instrum.* **83** 10D902
[65] Schmid G J *et al.* 2003 *Rev. Sci. Instrum.* **74** 1828
[66] Sio H W *et al.* these proceedings
[67] Rinderknecht H G *et al.* these proceedings
[68] Rinderknecht H G *et al.*2014 *Rev. Sci. Instrum.*, v. **85**, 11D901 (2014)

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.