LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-TR-739376

The ICF National Diagnostic Plan (NDP) 9/19/17

J. Kilkenny, G. Richau, C. Sangster, S. Batha, P. Bell, D. Larson, D. Bradley, R. Leeper, H. Herrmann, C. Bourdon, T. Hilsabeck

October 4, 2017

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

The ICF National Diagnostic Plan (NDP) 9/19/17

Summary: A major goal of the Stockpile Stewardship Program (SSP) is to deliver validated numerical models, benchmarked against experiments that address relevant and important issues and provide data that stress the codes and our understanding. DOE-NNSA has made significant investments in major facilities and high-performance computing to successfully execute the SSP. The more information obtained about the physical state of the plasmas produced, the more stringent the test of theories, models, and codes can be, leading to increased confidence in our predictive capability. To fully exploit the world-leading capabilities of the ICF program, a multi-year program to develop and deploy advanced diagnostics has been developed by the expert scientific community. To formalize these activities NNSA's Acting Director for the Inertial Confinement Fusion Program directed the formation and duties of the National Diagnostics Working Group (NDWG) in a Memorandum 11/3/16 (Appendix A).
The NDWG identified eight transformational diagnostics, shown in Table 1, that will provide unprecedented information from experiments in support of the SSP at NIF, Z and OMEGA. Table 1 shows how the missions of the SSP experiments including materials, complex hydrodynamics, radiation flow and effects and thermo-nuclear burn and boost will produce new observables, which will be measured using a variety of largely new diagnostic technologies used in the eight transformational diagnostics. The data provided by these diagnostics will validate and improve the physics contained within the SSP's simulations and both uncover and quantify important phenomena that lie beyond our present understanding.

Mission	New Observable	Technique	Acronym
Materials	Strength vs time of compressed Pu	> 4 images/costly target	SLOS
	Phase change compressed Pu - rates	Time dependent diffraction	TARDIS-time
	T of compressed Pu	Extended x-ray fine structure	Hi Res
Complex Hydro.	3D structure at ~ 50 keV	X-ray bands imager +SLOS	Wolter
Rad. Flow & Effects	T_e of Marshak wave	Deep u. v. Thomson scattering	UVTS
	Hard spectrum vs space & time	X-ray bands imager +SLOS	Wolter
Burn and boost	Time history of burn	Ultra-fast Cerenkov detector	GCD
	3D T_e and density vs time	Dilation tube + SLOS+Wolter	DIXI-SLOS
	3D burn, 3D mix vs time	3D neutron/γ imaging	NIS
	T_{ion} and areal density vs time	Neutron spectrum vs time	MRS-time
All	Hohlraum- density & T vs space & time	Deep u. v. Thomson scattering	UVTS

Table 1: How the missions of the SSP will be enhanced by new observables measured by the eight transformational diagnostics being developed under the guidance of the NDWG.

In addition to the transformational diagnostics, there are:

(1) a set of broad diagnostics coordinated across the ICF sites,
(2) a large number of local diagnostic associated with the three large facilities, NIF, OMEGA and Z.

This document is an update of the NDP as of 9/19/2017. The activities of the NDWG, its organization and leadership and the budgets are summarized in section II. The organization, progress and plans for the transformational diagnostics are in section III. The activities of the broad diagnostics are in section IV. Finally, the progress and plans for the local diagnostics on NIF, Z and OMEGA are in section V. Appendix A is the directive memo from NNSA establishing the NDWG, Appendix B is the summary of the NDWG meeting held 11/29-30/2016, and Appendix C is a viewgraph summary on the principles of operation of the eight transformational diagnostics.

II: Recent activities of the National Diagnostic Working Group (NDWG)

IIa: ICF Diagnostics: Background and Mission

Diagnostic development has been an ongoing activity in the ICF and High Energy Density (HED) program for multiple decades. With the construction and commissioning of the NIF, there have been regular NDWG meetings, initially to foster national participation in the diagnostics for the NIF and recently to coordinate research and development of HED diagnostics across the ICF sites for NIF, Z and OMEGA.

The national diagnostics development effort is divided into three groups:
1. Transformational Diagnostics: diagnostics requiring a major national effort with the potential to transform experimental capability for the most critical science needs across the complex.
2. Broad Diagnostics: diagnostic efforts and techniques requiring significant national efforts which will enable new or more precise measurements across the complex.
3. Local Diagnostics: important diagnostics that implement known technology for a local need and are identified by facility management responding to the needs of the local user community.

The NNSA ICF program supports stockpile stewardship through the four principal missions shown in table 1. The facilities also support National Security Applications (NSA) and basic science conducted mainly in collaboration with Universities. The decisions on which new diagnostics to develop depends on a combination of the diagnostic usage at the various facilities, the prioritized needs of the programs, the status of technology, and the requests from the user community. Each facility has a different process for making these decisions for local diagnostics. For transformational and broad diagnostics the development activities are prioritized, advocated for, and managed by the appointed leaders of the NDWG.

IIb: Recent activities and organization of the NDWG

(i) On November 29th and 30th , 2016 the NDWG met with 115 invited participants from LLNL, LANL, SNL, LLE, NSTec, GA, AWE, CEA, Universities, and Industry. Most of the work of the meeting was done in a set of eleven breakout groups. These were set up with directed scientific discussions to address specific questions posed by the NDWG leadership team which sought recommendations for augmentation and change to the National Diagnostic Plan. Recommendations from the eleven working groups are in Appendix B.

(ii) A national neutron Time of Flight (nToF) workshop was held in January 2016 and a second workshop was held in July 2017 at LLNL. Meeting summaries are available.

(iii) A workshop on X-ray Doppler Velocimetry (XDV) was held in August 2016 at LLNL.

(iv) Diagnostics workshops with the CEA were held in June 2016 at LLE and in May 2017 at Valduc, with action items and recommendations.

(v) The leadership group of the NDWG met in December 2016 to review progress on the NDP. The group briefed NNSA on the NDP plan in D.C. on 12/13/16.

(vi) The NDWG leadership group met at SNL on 3/13/17 to review progress.

(vii) The NDWG leadership group reported technical and financial issues to NNSA leadership (Njema Frazier and Dan Jobe) at SNL the same day.

(viii) The NDWG leadership group met at SNL on 6/7/17 to review progress and re-plan technical progress in light of the budget resolution for FY17 and the FY18 PB.

(ix) The NDWG leadership group reported progress to the NNSA at the ICF Execs Meeting in DC on 6/14/17.

The core leadership of the NDWG as appointed by the ICF Execs are Joe Kilkenny (GA), Greg Rochau (SNL), Craig Sangster (LLE) and Steve Batha (LANL) with consistent support from Perry Bell, Doug Larson and Dave Bradley(LLNL), Ray Leeper and Hans Herrmann (LANL), Chris Bourdon (SNL), and Terry Hilsabeck (GA).

IIc: NNSA Budget Actions on Diagnostics

Diagnostic activities in the NNSA ICF program are contained within Major Technical Efforts (MTE 10.3), Diagnostics, Cryogenics and Experimental support. The NDWG leadership provides information to the NNSA on the necessary resource allocations to execute the NDP as described in the NNSA Memorandum of 11/3/16 (Appendix A). NNSA has identified Diagnostics as a growth area. The text in the NNSA FY 2017 Presidents' Budget (PB) Request explains the reason for the proposed budget increase in FY2018 as:

"Diagnostics, Cryogenics, and Experimental Support:

The increase supports the National Diagnostics Plan in design, engineering, and implementation of transformation diagnostics – which tests the first x-ray gated single line-of-site measurement on Omega, deploys Optical Thomson-scattering diagnostics at NIF and Omega, and develops Gallium-Arsenide diodes for x-ray detection on hybrid complementary metal-oxide semiconductor (hCMOS) cameras.

FY 2018 vs FY 2016: +19,328 ($K)"

The NNSA PB is guidance for the site managers (ICF Execs). The NDWG Leadership group's role is to provide recommendations to the NNSA and ICF Execs on the resource allocation for diagnostics required to develop the necessary new capabilities and maintain a balanced program at their respective sites. The NDWG is grateful for the support of NNSA and the recommended funding increase.

III: Transformational Diagnostics

Section IIIa is an overview of the transformational diagnostics. Section IIIb is a summary of the achievements and plans for each of the eight transformational diagnostics.

IIIa: Overview of the Transformational Diagnostics

The NDWG defined Transformational Diagnostics as those requiring a major national effort with the potential to transform experimental capability for the most critical science needs across the complex. In early 2015 a set of transformational diagnostics identified as adding to the critical science needs was identified as shown in table 2.

Transformative diagnostic	Collaborating Institutions	New capability
Single LOS (SLOS) imaging	SNL, GA, LLNL,LLE	Multi-dimensional shape and spectra with unprecedented time and space resolution for fusion, Pu strength, and radiation effects sources
Optical Thomson Scattering	LLE, LLNL, LANL, NRL	Localized plasma conditions and turbulence in hohlraums and Laser Direct Drive ablation plasma. Additional uses include plasma conditions at low density for rad flow studies and many discover science applications.
3D n/gamma imaging	LANL, LLNL	3D shape & size of both burning and cold compressed fuel
Gamma spectroscopy	LANL, AWE, GA, LLNL	Fusion burn history allowing inferred pressure with increased precision and measured truncation of burn from degradation mechanisms such as mix and loss of confinement.
Time resolved neutron spectrum	MIT, LLNL, GA, LLE	Time evolution of the fusion burn temperature and areal density
Hi Res. X-ray spect.	LLNL, LLE, PPPL, NSTec, SNL	Time evolution of electron density, temperature, and mix in the hot fuel. Also enables measurements of time dependent temperature of compressed material in equation of state studies.
Hard x-ray imaging	SNL, LLNL, NASA, Harvard	High energy source distribution and space-resolved plasma conditions in the hot plasma. Also enables high spatial and temporal resolution for radiography to infer material strength.
Time resolved diffraction	SNL, LLNL, LLE	Time evolution of material structure (including weapon materials) and compression at high pressure. Also enables more efficient facility use through multiple measurements on a single shot.

Table 2: The eight transformational diagnostics, institutional involvement & missions.

This set of diagnostics was reviewed by an independent group of experts in 2015 who reported to NNSA on the relative merit and urgency of each proposed capability (report is available). The NDWG monitors, on a quarterly basis, progress on these eight transformational diagnostics as described in section II and makes recommendations to the sites in terms of development priority and resource requirements. There is a simplified description of these diagnostics starting on page 41 of NNSA's 2016 Inertial Confinement Fusion Program Framework DOE/NA-0044, and in Appendix C.

Each category of transformational diagnostics can mean many actual diagnostics at some or all of the three major facilities. The plans for implementation consist of many phases. Table 3 is the present schedule for the transformative diagnostics. This plan is largely consistent with the expected budgets in FY18 depending on the implemented site allocations and distributions relative to other funding priorities. The two red arrows were added from the last meeting of the NDWG leadership group and represent a strong recommendation to advance the schedule of these diagnostics in order to be responsive to the needs of the 2020 ICF review.

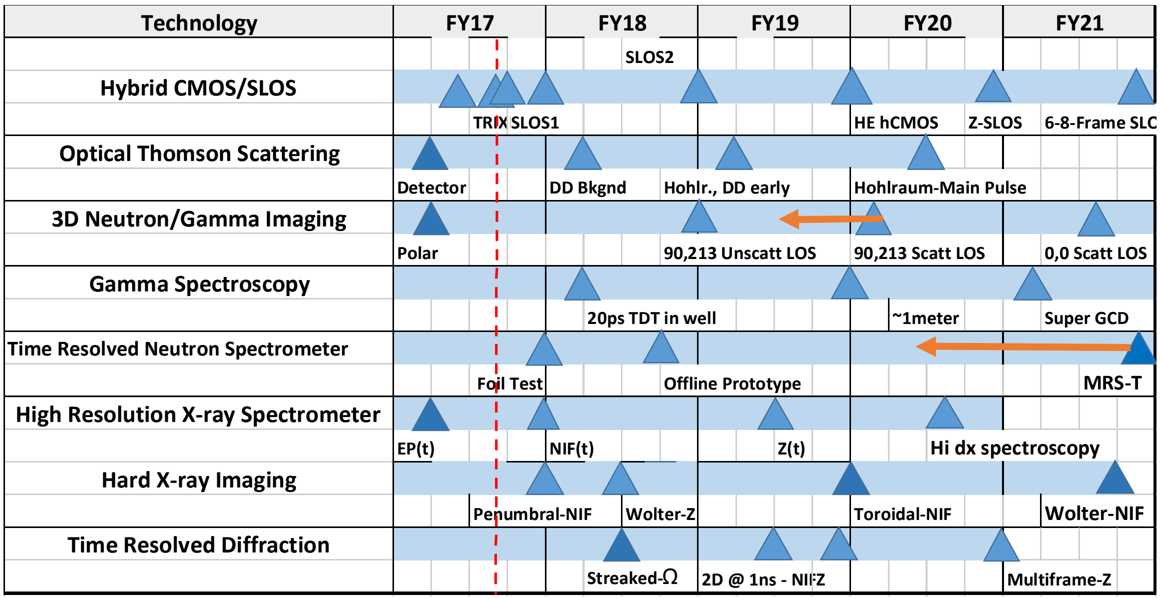


Table 3: Schedule for the transformational diagnostics. The acronym definition is below.

SLOS – Single Line Of Sight time gated detector, initially four frames.
SLOS1 – 4-frame SLOS built for use in a manipulator on NIF that will be used with pinholes and then the Crystal Backlit Imager (section V-1).
TRIXI – 4-frame SLOS on OMEGA.
SLOS2 – 4-frame SLOS built for the KirkPatrick Baez x-ray microscope on NIF
HE-hCMOS – hCMOS cameras with enhanced sensitivity to high energy x-rays using GaAs diode material.
Z-SLOS – SLOS for spherical crystal imaging on Z
6-8 frame SLOS – SLOS with an upgraded hCMOS back-end for more frames and faster time resolution.
DD Bkgnd – Measurement of Direct Drive background plasma light emission level
HOHLR,/ DD early – 5w Optical Thomson Scattering from a hohlraum or a Direct Drive plasma early in a shaped "ignition " pulse.
Hohlraum-Main Pulse – 5w Optical Thomson Scattering from a hohlraum during the main laser pulse of ignition-relevant targets
Polar – Imaging of un-scattered neutrons from (near) the north pole on NIF
90,213 Unscattered LOS – Imaging of un-scattered neutrons at on 90,213 line of sight.
0,0 Scattered LOS – Imaging of down-scattered neutrons from (near) the north pole.
20ps TDT in well – Time history of gamma ray emission using the Time Dilation Detector in a well at 3.9 m from target chamber center.
~1 meter – Time history of gamma ray emission at ~1 m from target chamber center
Super GC – Upgraded Gamma (Cherenkov) ray detector with 4 channels for low-resolution gamma ray spectroscopy.
Z(t) – High resolution spherical crystal spectrometer coupled to an hCMOS camera on Z

EP(t) – Time resolved high resolution x-ray spectrometer on OMEGA EP
Hi dx Spectroscopy – High spatial resolution (dx) x-ray spectroscopy.
Penumbral NIF – Penumbral apertures on NIF for high energy/resolution imaging.
Wolter-Z – First implementation of Wolter optics on Z for >15 keV x-ray source shape.
Toroidal-NIF – Toroidal optics for high resolution spatial distribution of hot spot electron temperature on NIF.
Streaked Omega – Phase and compression evolution using x-ray streak camera measurements on Omega.
2D @ 1ns - NIF – Coupled hCMOS cameras to NIF diffraction platform for multi-frame phase.
Single Frame - Z – Diffraction on Z with a single x-ray frame.
Multi-Frame - Z – Diffraction on Z with multiple frames on a single shot.
MRS-T _- Time resolved Magnetic Recoil Spectrometer
Wolter NIF – 20 -30 keV Wolter x-ray microscope with ~5 μm resolution

<u>IIIb: Achievements and plans for each of the eight transformational diagnostics.</u>

IIIb-1: Single Line-of-Sight (SLOS) Imaging

Two new technologies developed within the ICF program are revolutionizing gated x-ray detectors. These technologies are pulse-dilation tubes developed in collaboration between General Atomics, Kentech Instruments, and LLNL, and fast-gated hybrid complementary metal-oxide-semiconductor (hCMOS) sensors developed at SNL. Coupled together, these technologies provide the transformative capability of time gating for multiple frames along a single line-of-sight (SLOS) at gate times as short as 10 ps. Used separately, the hCMOS sensor can provide direct detection of multi-keV x-rays at gate times > 1 ns. Pulse-dilation SLOS framing cameras are transformative because they enable time-gated detection at speeds never before possible using curved crystal and multi-layer mirror optics, which can have superior spatial resolution and energy selectivity over pinhole/slit optics, but are too expensive or take up too much space to create an array of many images along many lines-of-sight. The hCMOS sensors are transformative because they provide multi-frame direct detection of x-rays at nanosecond frame-rates in a technology that can be customized for the x-ray energy of an imager or a spectrometer. Figure 1 shows pictures of the first pulse-dilation SLOS detector coupled to an hCMOS sensor.

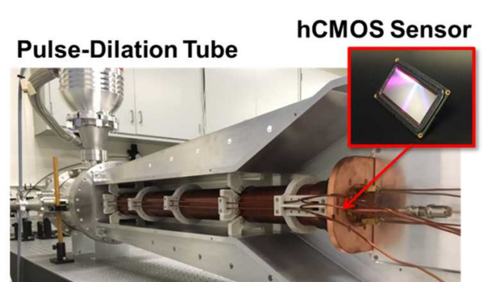


Figure 1: Picture of the first pulse-dilation SLOS detector

The way time dilation works is shown in Appendix C. X-rays cause photo-electron emission from a photocathode. The photo-electrons are accelerated across a small gap by the application of an electric field that ramps down in energy over time. The accelerated electron pulse drifts down magnetic field lines causing the electrons of different energy to separate in their time-of-flight while maintaining spatial orientation. This time-separation (pulse-dilation) allows the electron-sensitive hCMOS sensor to sample the images at a rate of 1-2 ns per frame to achieve 10-40 ps resolution of the incident x-rays. Actual gate time is set by need.

Time dilation technology without the hCMOS detectors is used in the DIXI (dilation x-ray imager) detector on NIF for about 2 years. The first pulse-dilation SLOS systems have recently been used on OMEGA (TRIXI) and is expected to be used at the end of September on NIF (SLOS1) for hot-spot imaging in Laser Direct Drive and Laser Indirect Drive respectively.

An early version of a stand-alone hCMOS sensor has been used on NIF since 2015 (H. Chen et. al. Rev. Sci. Instrumen. **97**, 11E203 (2016)). Recently hCMOS sensors are being deployed on Z for both gated opacity spectra and imaging of the preheat in Magnetic Direct Drive ICF. Each of these applications uses an hCMOS sensor capable of acquiring two frames per half of the sensor for a total of 4 frames on 2 lines-of-sight. In FY18, these hCMOS sensors will be replaced with a new generation capable of 4 frames along each line-of-sight.

Future plans include developing a pulse-dilation SLOS for Z by FY2020 and a 6-8 frame hCMOS camera by FY2021. Hard x-ray (> 20 keV) detection is important for SSP diagnosis. Our existing hCMOS detector uses a Si based pixelated diode with low efficiency for hard x-rays and so we plan a prototype 10-30 keV x-ray-sensitive version by FY2020 probably using a GaAs diode. Plans for the utilization of this SLOS capability include coupling to Kirkpatrick-Baez, spherical, and toroidal optics for hot-spot imaging, gated multi-frame backlighting, and spectroscopy of ICF implosions. This capability will also be used for time-resolved diffraction as a direct replacement to time-integrating image plate.

IIIb-2: Optical Thomson Scattering

The time evolution of the hohlraum plasma density (ne), temperature (Te), flow velocity and turbulence levels are critical parameters for understanding the x-ray drive for all HED hohlraum applications. Likewise, for Laser Direct Drive (LDD) in long scale length plasmas such as LDD on NIF, measurement of ne, Te and turbulence above the critical density is important for understanding the drive pressure and its uniformity. These fundamental parameters will be uniquely measured, without recourse to integrated rad-hydro models, with Optical Thomson Scattering (OTS) on NIF. These parameters need to be measured at high densities (ne is calculated to be > 10^{21} e/cc in a NIF hohlraum) and this leads to the requirement for an ultraviolet Thomson scattering probe laser beam in order to avoid significant absorption and refraction. Background plasma emission and other sources of non-Thomson scattered light indicate that to exceed a signal-to-noise of unity the Thomson scattering probe laser must be 1-10J in 1ns at 210 nm, see J. S. Ross et al., Rev. of Sci. Instrumen. **87**, 11E510 (2016).

There are also less challenging experimental configurations which can benefit from OTS on NIF and are benefitting from 4w OTS on OMEGA, for example see J. Katz et al., Rev. Sci. Instrum. **83**, 10E349 (2012)]. These include source development for radiation effects experiments, experiments designed to study energy transport in foams, and collision-less shocks in colliding plasmas. OTS has been implemented on Nova, Trident, JLF and OMEGA although in less stressing conditions than an ignition hohlraum and LDD on NIF. OTS on NIF is therefore a transformative diagnostic because the short wavelength of the probe opens new windows in plasma density even after five decades of Thomson scattering from high temperature plasmas.

For OTS on NIF an ultraviolet probe beam will be generated by 5^{th} harmonic conversion of a glass laser beam. A separate 100J class, 1.06 µm laser beam line has been through the rigorous design review process for NIF including frequency conversion to 210 nm and delivery to target chamber center. Installation of a NIF preamplifier module (PAM) in NIF to provide the seed 1.06 micron laser energy is in progress.

Although OTS is used widely in ICF and magnetic fusion research, our high densities drive us to use 210 nm. Work at LLE in FY16 measured conversion efficiencies from 1.06 micron to 210 nm, albeit with smaller beams, of 10-20% [I. A. Begishev et al. (CLEO:2016 © OSA 2016)]. Full size beam conversion tests are presently underway. The detector for the scattered light is a dual spectrometer multiplexing onto an ultraviolet sensitive streak camera. The detector was designed and built in FY16 [P Datte et al., (IFSA 2015) IOP Publishing], and is shown in Fig 2. The detector has been used to measure the background levels for NIF hohlraums and will be used soon to determine the level of emission for NIF scale LDD. The detector has already been used for 3w OTS on NIF from a relatively low density plasma.

Figure 2: OTS detector for a DIM on the NIF.

IIIB-3: 3D Neutron Imaging System

The objective of the Neutron Imaging Diagnostics is to fully characterize the three-dimensional (3D) fuel assembly at stagnation by neutron (primary and scattered), x-ray, and gamma-ray images. As of 2017 the neutron imaging system (NIS) at NIF views implosions from an equatorial view and a near polar view. The systems are composed of two basic pieces: a pinhole aperture array that is used to form the neutron, x-ray and gamma images and a detector system that is used to record the image formed by the pinhole array. A scintillator-based detector with gated cameras on the existing equatorial line-of-sight allows the collection of two independently timed images. Typically, one detector is gated to view the 14 MeV neutrons and provides information on the size and shape of the hot spot. The second detector is gated at a later time to measure the source distribution of lower energy and lower intensity neutrons (which arrive later), typically in the 6-12 MeV range, to provide information on the distribution of the cold fuel. In addition image plate detectors installed both for the equatorial and polar lines-of-sight provide a time integrated neutron image, which in essence is a 14 MeV neutron image of the burning hotspot. The equatorial line-of-sight image plate detector also records a burn-weighted x-ray image of the implosion allowing study of mix effects. Figure 3 shows reconstructed volume distribution of the primary neutron production and cold-fuel density from a recent high-yield experiment at NIF (N170601-002).

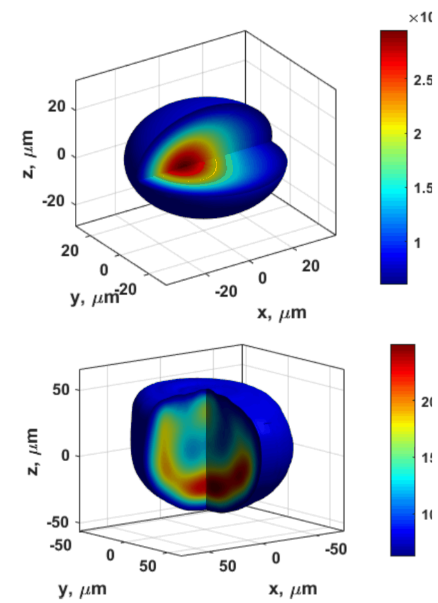


Figure 3. Neutron Imaging System provides distribution of the neutron production (top) and cold-fuel density (bottom) from a recent high-yield experiment at NIF (N170601-

To achieve the goals identified in the National Diagnostics Plan the following steps are planned to advance the Neutron Imaging System: 1) a new equatorial multi-spectral imager (primary and scattered neutrons, x-rays, & gammas), orthogonal to the existing systems , and 2) the existing neutron imaging systems will be upgraded to allow recording multi-spectral images. These advancements of the imaging system would provide a measure of the three dimensional structure of the hot spot, cold fuel and remaining ablator distributions. The collection of this data would enable the study of the effect of three dimensional asymmetry on the stagnation phase physics, providing a measurement of 3D asymmetry and performance to guide the development and validation of 3D models and simulations.

IIIb-4: NIF Gas Cherenkov Detector (GCD)

Gas Cherenkov Detectors, such as the Gamma Reaction History (GRH-6m) diagnostic on NIF, have been providing time-resolved measurements of gamma-rays from implosions for several years. The primary measurements have been fusion reaction history (based on DT γ at ~17 MeV) and ablator areal density history (based on $^{12}C(n,n\gamma)$ at 4.4 MeV). However, GRH-6m is limited in temporal resolution and sensitivity. The objective of the transformative diagnostic effort known as NIF GCD is to overcome these limitations in order to positively identify signs of alpha heating and/or performance degradation mechanisms such as mix and asymmetry.

As shown in Figure 4, GCD works by converting a small fraction of the incident gammas to relativistic electrons through Compton scattering off the electrons in a beryllium convertor inside the nose cone of a pressurized gas cell. These relativistic electrons, which then interact with the detector's fill gas, produce UV/visible Cherenkov light, which is measured by a photomultiplier tube (PMT). Current state-of-the-art PMT technology limits the temporal resolution to ≥100 ps which is also the approximate burn duration of an ICF implosion, although the gas cell itself is capable of much faster time resolution (~10 p

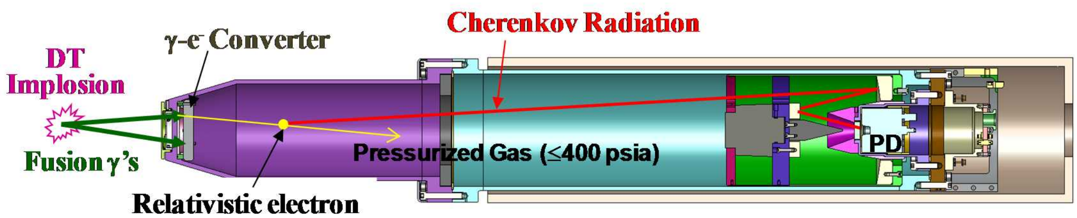


Figure 4: Schematic of the NIF Gas Cherenkov Detector.

The first phase of NIF GCD, now complete, consisted of installing a new detector GCD-3 into the NIF to 3.9 m well. Phase II consists of implementing a revolutionary new Pulse Dilation PMT (PD-PMT) technology in order to bring the resolution of the optical detector down to the 10 ps. The idea for the PD-PMT came from the NDWG meeting in 2014 using the time dilation concept. A prototype of the PD-PMT was demonstrated in collaboration with Photek/Kentech/Sydor at AWE in 2016. The production unit is being built and will be incorporated into GCD-3 in early 2018. The goal of Phase III will be to increase GCD-3 sensitivity several orders of magnitude by operating it on a TANDM diagnostic insertor in close to TCC. This will enable innovative time-resolved mix measurements which will discriminate between mix mechanisms (e.g., diffusion vs turbulence) and highly constrain implosion models. Experience from GCD-3 operations will be fed into the final phase of developing a NIF-specific "Super GCD" which can better handle the harsh radiation environment associated with indirect-drive.

IIIb-5: Time-resolving Magnetic Recoil Spectrometer (MRSt)

In support of the ignition experiments at the NIF, current neutron spectrometers routinely measure the time-integrated neutron spectrum, from which burn-averaged values of ρR, Y_n, and apparent T_i have been determined. Although these data have been essential to understand and improve the ignition experiments at the NIF, the current suite of spectrometers does not provide any information about the time evolution of the fuel assembly, hot-spot formation, alpha heating, and nuclear burn. This information will be obtained with the next-generation Magnetic Recoil Spectrometer (MRSt) through measurements of the neutron spectrum (12-16 MeV) with high accuracy (<5%), unprecedented energy resolution (~100 keV) and, for the first time ever, time resolution (~20 ps). The MRSt uses existing MRS principle and pulse-dilation-drift-tube technique instead of CR39 as the detector.

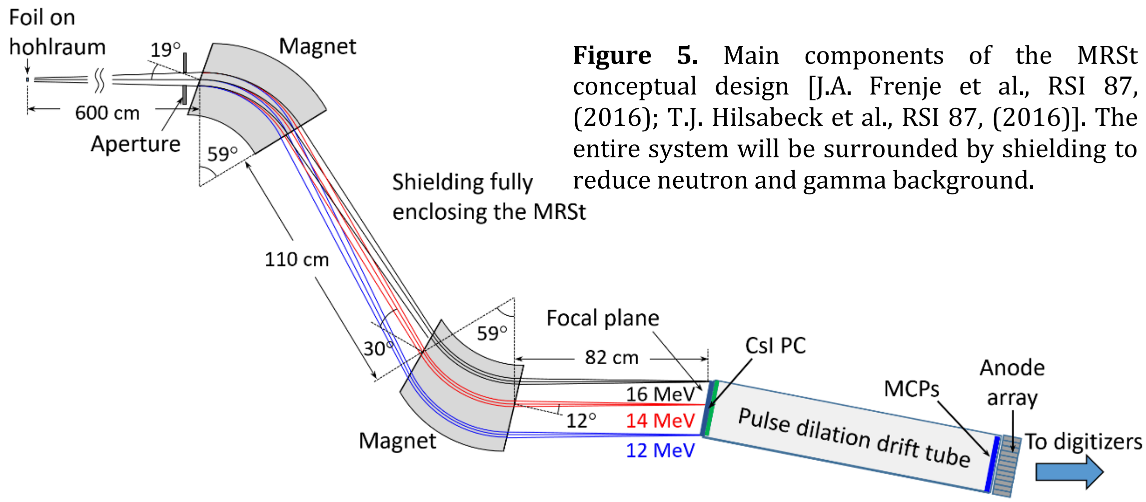


Figure 5. Main components of the MRSt conceptual design [J.A. Frenje et al., RSI 87, (2016); T.J. Hilsabeck et al., RSI 87, (2016)]. The entire system will be surrounded by shielding to reduce neutron and gamma background.

MRSt, uses (a) 20- to 40-μm-thick, 0.5-mm-diameter CH (or CD) foil, positioned on the outside of the hohlraum, for production of recoil protons (or deuterons) from incident neutrons; (b) two magnets, positioned outside the NIF target chamber, with opposing B-fields for energy analysis and focusing of forward-scattered recoil ions onto the focal plane of the spectrometer; and (c) a pulse-dilation drift tube with a CsI "photo"cathode positioned at the focal plane. In the CsI photocathode the recoil ions are converted into secondary electrons, which are subsequently accelerated by a spatially- and time-varying electric field that unskews and stretches the signal over a 1-m drift length. This signal is then amplified by MCPs and detected by an anode array.

The ion-optics and shielding designs are nearly complete. Offline tests of the other MRSt components are scheduled to be completed by mid-FY18. Tests of the CsI photocathode response to ions using the MIT-HEDP accelerator; tests of the foil-on-hohlraum concept using a NIF shot; and tests of the prototype pulse-dilation drift-tube with unskewing/dilation capabilities are underway. The MRSt is expected to be installed on the NIF by FY2021.

IIIb-6:High-Resolution X-Ray Spectrometer

High resolution spectroscopy is a powerful method to interpret the local plasma conditions through analysis of the relative strengths and shapes of x-ray emission lines emanating from various ion species in the subject plasma. Detailed analysis requires both a high resolving power ($E/\Delta E > 1000$) and good spatial and temporal resolution. High resolution spectrometers are planned for each facility in the next 2 years.

A high-resolving-power, streaked x-ray spectrometer for OMEGA EP is based on two diagnostic channels, each with a spherical Bragg crystal. Channel 1 couples a spherical Si220 crystal to an x-ray streak camera. Channel 2 couples a second, identical crystal to an x-ray charge-coupled device (CCD), allowing photometric calibration of the time-resolved spectrum. The instrument covers the spectral range 7.97 to 8.11 keV, centered on the Cu $K\alpha_1$ line at 8.05 keV. The time-resolved spectrometer is designed to achieve a resolving power of 2000 and a temporal resolution of 2 ps.

Instrument installation and activation on OMEGA EP is complete. The instrument capabilities have been demonstrated by resolving the Cu $K\alpha_{1,2}$ doublet on high-power shots. Figure 6 shows initial streak camera data from cold and hot targets. In the highest energy density conditions, outer shell ionization affects the energy and shape of the Kα line. These data confirm the required performance of the Bragg crystal and the fidelity of the instrument shielding on high-power shots. Studies are underway to quantify the signal limits that are allowable before space-charge broadening affects the integrity of the streaked signal.

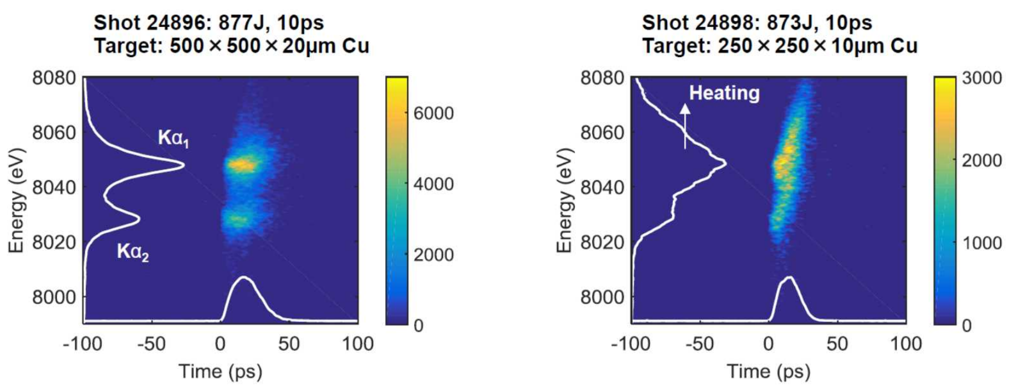


Figure 6. Time-resolved Cu $K\alpha_{1,2}$ emission spectra for high-power interactions with 1 and 10 ps pulses.

On Z, a high resolution spectrometer utilizing spherically-bent crystals is operational in time-integrated mode and provides detailed spectra with excellent spectral resolving power (>3000) and moderate spatial resolution (~50 microns). This spectrometer is optimized for measurement of iron and cobalt spectra, which are used as coatings and dopants in Magnetic Direct Drive (MDD) targets. Future plans are to add an hCMOS detector to this spectrometer by FY19 for time-gated measurements at ~1 ns resolution. An example of the Fe He-alpha line and associated satellites is shown in figure 7.

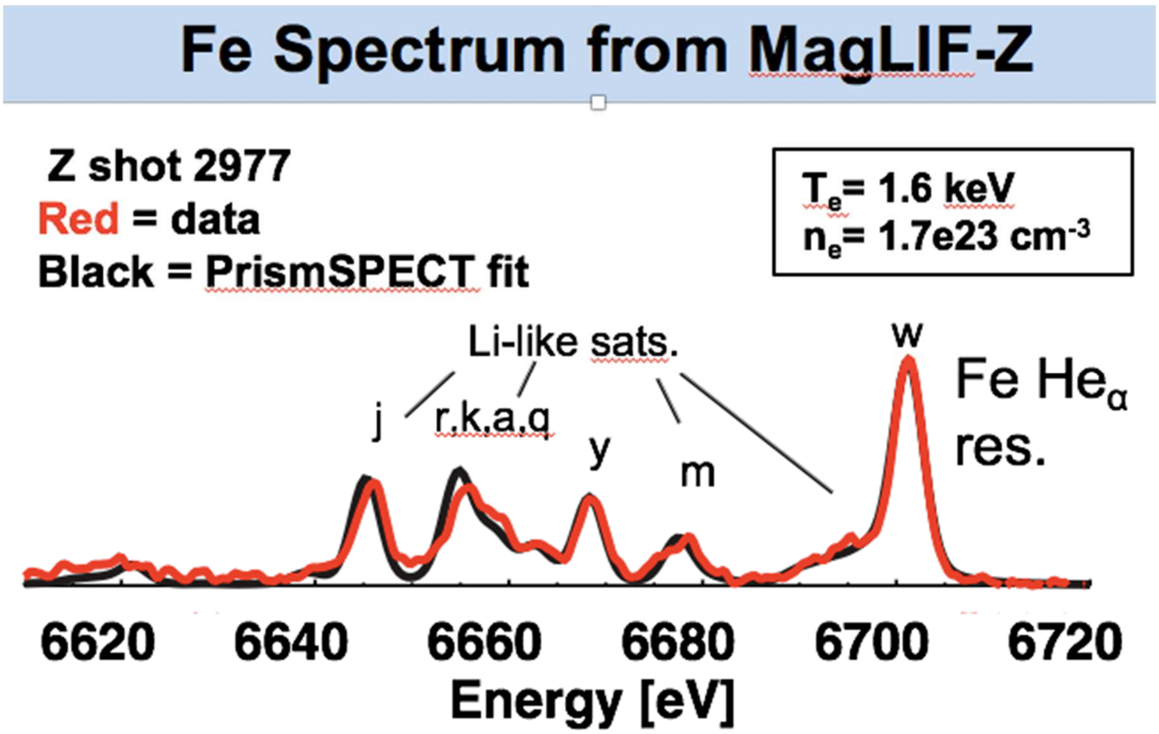


Figure 7. Example iron spectra from the high-resolution x-ray spectrometer on Z.

On NIF a 3 channel high resolution time resolved x-ray spectrometer utilizing two conical crystals for time resolved channels and one cylindrical crystal for a time integrated channel is in the final stage of characterization at the Princeton Plasma Physics Laboratory. This diagnostic is expected to measure line emission from dense plasmas in the 12 to 16 keV regime with a resolving power of $E/\Delta E \sim 2100$ for time resolved and 1300 for time integrated spectra in Q4 FY17.

IIIB-7: Hard (15-60keV) x-ray imaging (Wolter)

There is a strong need for highly resolved (spatial and temporal) hard (> 20 keV) x-ray imaging with narrow (~1 keV) bandwidth at HED facilities. This capability is required for core self-emission imaging for ignition implosions, x-ray source development for outputs and effects, and materials strength experiments.

For LID implosions on NIF the electron temperature distribution can be measured in a band that is unaffected by the opacity of the colder surrounding shell requiring measurements at energies > 20 keV. An imaging instrument with sufficient spatial (~10 micron), temporal (~10 ps), and spectral (~1 keV) resolution operating at three different energy bands across the range of 20-30 keV could provide spatial profiles of the temperature distribution. Due to the high temporal, spatial, and spectral resolution, the instrument would also need a high solid angle in order to achieve sufficient signal-to-noise in the image. As a first step toward this goal, a set of penumbral imagers with the array of apertures close to the implosion on NIF can achieve a large enough solid angle to obtain time integrated images at ~ 20 keV with a bandwidth of about 3 keV as shown in Fig 8.

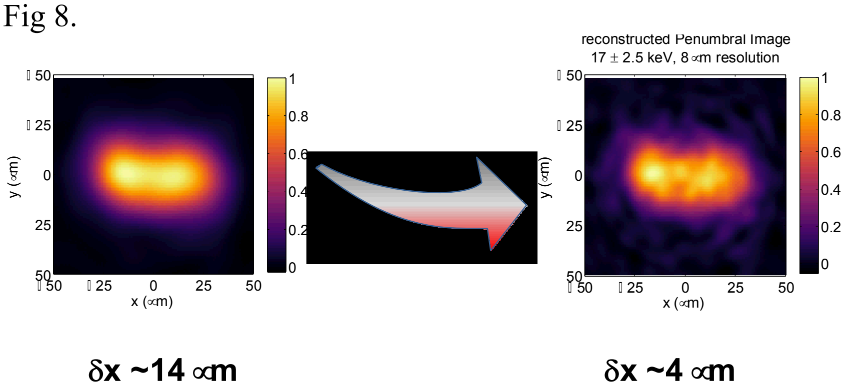


Figure 8: Example pinhole image (left) with ~14 micron spatial resolution and a comparison penumbral image (right) with ~4 micron spatial resolution.

As a second step towards multi-band, high-energy, high-spatial-resolution imaging on NIF, toroidal optics are being developed in collaboration with the French CEA. These optics have the additional benefit over penumbral apertures of being more monochromatic and perhaps more compatible with SLOS due to the lower overall magnification compared to penumbral apertures that must be placed very close to the target. A toroidal imaging system is presently under consideration for NIF by the end of FY19.

High energy (> 15 keV) x-ray imaging is needed on Z in support of K-alpha x-ray source development using z pinches, an important technique for Outputs and Effects research, presently diagnosed with 1-D space resolving transmission crystal spectrometers and low-resolution pinhole imagers. Multi-dimensional, narrow band imaging of these sources is necessary to determine the true source distribution in the z pinch in order to build understanding of the kinetic processes in these complex plasmas and for benchmarking simulations that will be used to optimize the output. Requirements are a 5x5x5 mm field-of-view (FOV), < 200 micron spatial resolution, and a relatively narrow energy band (~1 keV) around 22.2 keV- silver K_{α}. To meet these requirements a multi-layer replica Wolter optics is being built using a broad collaboration of NASA Marshall, Harvard and LLNL capitalizing on previous investments. This will be a magnification ~3 Wolter x-ray microscope viewing along a 0-degree port on the Z target chamber with the optic ~75 cm from the source. The mandrel for the replica process has been manufactured at NASA Marshall and is currently at Harvard being coated. Optic fabrication and characterization will be complete in early FY18 ready for use on Z in mid FY18.

IIIb-8: Time-Resolved Diffraction

The development over the last decade to conduct nearly isentropic dynamic compression experiments on HED facilities has dramatically increased the range of conditions over which materials can be studied. This has especially enabled the study of materials at very high pressures that remain in the solid state and provides the opportunity to investigate solid-solid phase transitions in a wide range of materials along with investigations of the solid-liquid phase boundary at extreme density and temperature. Such conditions also necessitate the understanding of phase transitions under dynamic loading. For phase information, x-ray diffraction is the most-widely used method to determine the structure of a solid material.

X-ray diffraction platforms are successfully used on OMEGA and NIF for measuring the phase of a material at high pressure. These systems use a multi-keV x-ray source produced by a high-intensity-laser pulse. The x-ray pulse diffracts through a sample and the diffraction pattern is recorded on image plate (IP) that fills up a large fraction of the solid angle. Time resolution is obtained from the x-ray source, which is typically a single pulse of ~1 ns duration. The ability to extend existing diffraction platforms to multiple time steps provides the transformative capabilities to measure multiple phase changes in a single experiment as well as observe the kinetic effects across a phase transition (Figure 9). The former requires at least 2 distinct x-ray pulses and has already been demonstrated in experiments on NIF by spatially separating the x-ray sources so they produce diffraction patterns at different locations on the IP. The latter requires either many x-ray pulses or a long duration x-ray pulse and a time-resolving detector. Multiple approaches are currently under development to realize this capability including the implementation of a streak camera at the IP location on OMEGA-EP in FY18 and the use of both an x-ray streak camera and hCMOS for direct x-ray imaging of the diffraction pattern on NIF in FY19-20.

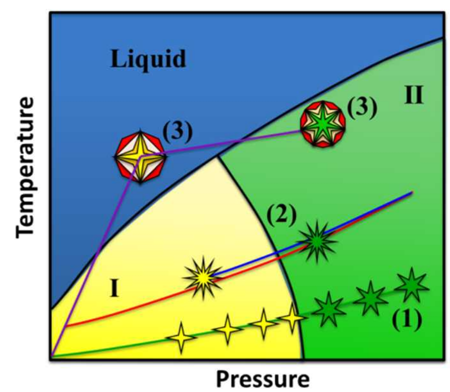


Figure 9: Hypothetical phase diagram. Goals include measuring (1) kinetics across a solid-solid phase boundary, (2) compression and release across a phase boundary, and (3) liquid-solid phase transitions

Parallel to these efforts is the establishment of an x-ray diffraction capability on the Z Facility. This is an important and transformational capability because Z provides both a larger sample size and a lower strain-rate than NIF for achieving Mbar pressures. In the long run, it will be important to measure phase changes and the associated kinetics across a range of strain rates. The Z platform uses the Z Beamlet Laser to produce a multi-keV x-ray source, but cannot use IP as a detector close to the sample because of the large debris environment. The initial implementation in FY18 may instead utilize a spherical crystal to image the diffraction pattern from 6-8 keV x-rays onto IP in a protected location. Future development will include the use of a fast phosphor close to the sample coupled to a multi-frame camera for time-resolved diffraction measurements in ~FY20.

IV: Broad Diagnostic Efforts

The NDWG defined a class of diagnostics or diagnostic related activities which benefits from significant national efforts and will enable new or more precise measurements across the complex. These are: Precision nToF, Mix and Te , Image Analysis, Hard X-Ray Detectors , X-ray Doppler Velocimetry, (XDV) and Synthetic Data.
These efforts, which are mainly in the scientific stage as opposed to engineering phase, were by design the subject of much of the broad NDWG meeting and are well documented in appendix B "Summary of the National Diagnostic Working Group (NDWG) Meeting, LLNL, November 29-30, 2016"

V: Local diagnostic development efforts at NIF, Z and OMEGA

V-1: Local Diagnostic Development on the National Ignition Facility

New local diagnostic capabilities on the National Ignition Facility (NIF) are aimed at improving our understanding of the evolution of high energy density plasmas for stockpile stewardship, National Security applications and discovery science. The transformational diagnostics are also a major effort at LLNL but that is discussed in section III. Table 4 is a representation of existing major local efforts and a draft of the diagnostic effort envisaged for FY18 and FY19.

Major NIF local diagnostic	FY17				FY18				FY19			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
NSS												
FFLEX move												
Dante upgrade												
dHiRes - DISC												
Upgrade DISC												
X-ray optic calibration facility												
SPnToF screening												
Continuum spectrometer												
Aperture imaging (penumb.& t. mount phole)												
CBI												
HGXD-Rad Hard Camera												
Z_VISAR												
Prec.nToF												
RTNADS												
Contaminated Control VISAR												
U.V. Interferometry-polarimetry												
EXAFS spectrometer												
DIXI-polar												
Scattered light diagnostic DD - 5 systems												
Toroidal x-ray imager												
Crystal calibration facility												
Flat fielding source												
SPBT- upgrade												
Rad hard DISC												
NIF-OHRV NHRV												
Imaging x-ray spectrometer												
SPEC 5 nToF												
SPEC 6 nToF												
VIRGIL-time												

Table 4: Local diagnostic effort on NIF. Strength of color approximates the level of effort.

The majority of the development activities in FY18-19 are focused on the development of x-ray, neutron and optical diagnostics. Here is a brief description of these capabilities and their applications:

NSS: NIF Survey Spectrometer: This is a transmission crystal geometry spectrometer, designed to provide time integrated spectrally resolved data over a large energy range (6 to 260 keV).

FFLEX move: This is a filter fluorescer diagnostic that measures the absolute radiant hard x-ray power vs time in ten spectral bands (18 keV to 400 keV). The existing diagnostic will be moved forward to provide room to install and operate a new NIF target positioner (TANDEM).

Dante Upgrade: The existing broadband, time-resolved x-ray spectrometers will be upgraded to (a) add clipping circuits to clamp highest voltage output below damage threshold of digitizers (mitigation against damaged filters); (b) add broadband multi-layer mirrors to improve measurements of "hard x-ray, M" band emission (1.5-3keV) from NIF hohlraums.

DHiRes - DISC: This is a high resolution time resolved x-ray spectrometer utilizing conical crystals to measure line emission from dense plasmas doped with Kr (Heα lines of Kr in the region 12.9-13.5 keV and Heβ lines of Kr in the region, 14.9-15.6 keV). There is an absolutely-calibrated time-integrated channel that covers both regions.

Upgrade DISC: The existing DIM Insertable Streak Camera (DISC) will be upgraded with improved electron optics to improve the spatial resolution over the whole 24mm active area of the cathode. The microchannel plate fiber optic detector will also be replaced with a direct electron detection CMOS detector.

X-ray Optical Calibration Facility: Local x-ray calibration of NIF crystals and mirrors to verify instruments behaves according to specifications, Specifically this facility will ensure instruments performs over the required energy range with correct point spread function. This facility will also be used to check performance of instruments throughout their lifetime on NIF target experiments.

S. P. nToF screeening: Installation of additional shielding around the existing South Pole neutron Time of Flight spectrometer (SPnToF) to provide local shielding that will reduce the effect of neutron induced gamma radiation that can be seen from the detector. The main source of this background is from neutron induced gammas from the floor above the south pole nToF.

Continuum Spectrometer: Single conical time resolved crystal spectrometer designed to measure continuum emission in region of 20-30keV, which can be used to infer electron temperature in an optically thin plasma.

Aperture Imaging: Variation on pinhole imaging, using penumbral imaging techniques and target mounted pinholes to increase spatial resolution (<5 micron) when imaging plasmas for ICF and HED applications.

CBI: Crystal Backlit Imaging; this diagnostic uses spherical Bragg crystals to provide narrow band (dE/E < 0.5%) high resolution imaging (<10 micron) at discrete photon energies (6keV – 16keV) for ICF and HED applications.

HGXD-Rad Hard Camera: Replace the optical film that is used in the current Hardened Gated X-ray framing camera Diagnostic (HGXD) with radiation hardened CMOS sensors to increase useful neutron yield ceiling of these x-ray imaging cameras to ~ 10^{17} neutrons per shot.

Z_VISAR: This is 1-D imaging open-beam VISAR system developed in collaboration between SNL and LLNL for use on Z. The primary application is measuring current delivery to MDD-ICF targets.

Prec.nToF: Precision Neutron time of Flight diagnostic will replace existing Bibenzyl scintillator as the neutron detector with device using Cherenkov emission in quartz crystals. This fast optical signal reduces the instrument response function (IRF) from its current many nano-seconds to ~350 of pico-seconds. This effectively reduces the DT Tion systematic uncertainty due to the IRF to around 50 eV. Further, since the crystal is also sensitive to gammas produced at bangtime, the detector will also improve the accuracy of fluid velocity measurements by through direct measurement of the neutron-gamma flight time difference along a given flight path.
rTNADS: The real time Nuclear Activation Diagnostic uses in situ Zirconium activation coupled to photomultipliers to provide a real time spatial measurement of the neutron flux at the NIF target chamber after a high yield shot (>5e14 neutrons) . This diagnostic will provide a spatial map of relative unscattered neutron flux at least 24 locations around the NIF target chamber. This data is designed to be used to infer the uniformity of the compressed DT fuel in an ICF implosion.
Contaminated Control VISAR: This diagnostic modifies the VISAR debris shield so that VISAR can be used whenever NIF is used to study hazardous material such as "high Z".
EXAFS spectrometer: High resolution spectrometer for measuring Absorption Fine Structure near absorption edges. This is a sensitive temperature diagnostic in shock heated plasmas. This design allows crystals to be changed to look at the different absorptionedges.
DIXI Polar: "Dilation Imager for X-rays at Ignition". A DIXI high temporal resolution x-ray imager will be mounted on the Polar DIM of the NIF target chamber. This diagnostic utilizes a time dilation drift tube to obtain x-ray images of high yield implosions from the pole with a time resolution better than 10 ps. This kind of time resolution is necessary because as the yield increases, the duration of x-ray emission reduces to 100 ps.
Scattered light diagnostic for direct drive (DD)- five systems: Scattered light diagnostic to measure angular distribution of scattered laser light principally from Direct Drive laser illumination experiments on NIF.
Toroidal: Toroidal curved x-ray imaging microscope for quasi monochromatic radiography of plasmas and shocked material with <10um resolution and dE/E ~0.5%
Crystal calibration facility: X-ray calibration station inside NIF facility, to measure absolute sensitivity and sensitivity vs x-ray energy of NIF spectrometer snouts in the geometry in which they are used and to track performance vs time.
Flat fielding facility: A 5w laser is used to characterize and correct for spatial and temporal gain non uniformities of gated x-ray framing cameras. The 30ps laser is used to step through the gating pulse of the imager to build up a gate profile. A sum of these gate profiles produces a 'quasi-flat field' of the instrument.
SPBT upgrade: South-Pole Bang-Time will be upgraded to provide new HAPG crystals and Indium Phosphide detectors that that will characterize the time of peak x-ray capsule emission at both 15 and 30keV. This will be used to obtain a slope temperature measurement at x-ray energies that are transparent to the imploded shell in high convergence implosions.
Rad hard DISC: Radiation hardened x-ray streak camera (DISC),using similar electronics to the hardened x-ray framing cameras (HGXD), that can be used for

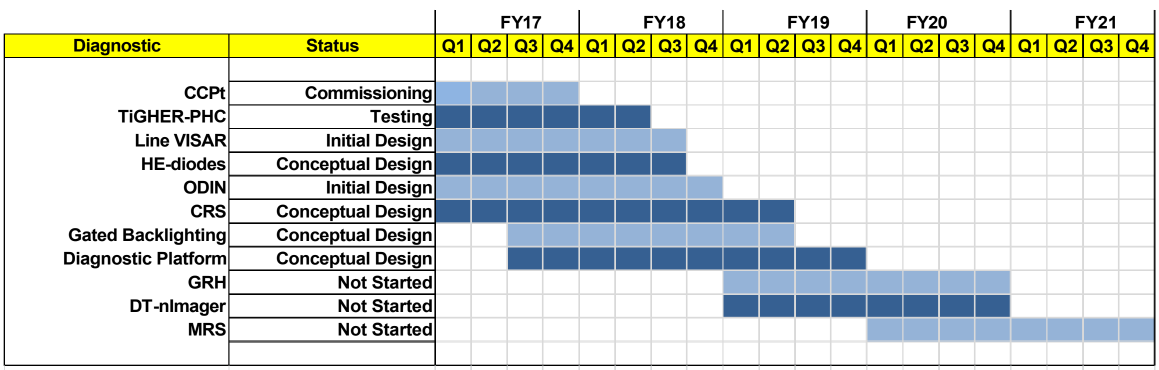
spectroscopic and radiographic measurements in high neutron yield environments (>1e14 neutrons).
NIF_OHRV(=NHRV): NIF High Resolution Velocity Interferometer. This is a 2-Dimensional diagnostic for measuring shock uniformity in ICF ablators such as CH, HDC and Be at pressures in 1 to >20 Mbar range with gate times < 40 ps.
Imaging spectrometer: High spatial and spectral resolution imaging spectrometer for characterizing temperature gradients in HED plasmas.
SPEC5 nToF: 5th Neutron time of flight diagnostic in a location opposite to existing to nToF detectors. This diagnostic will help to increase accuracy of fluid velocities in high convergence ICF and HED implosions
SPEC6 nToF: 6th Neutron time of flight diagnostic in a location opposite to existing to nToF detectors. This diagnostic will help to increase accuracy of fluid velocities in high convergence ICF and HED implosions
VIRGIL time resolved spectrometer: Adding time resolution to the VIRGIL X-ray spectrometer for characterizing hohlraum emission spectrum in soft x-ray regime.
RACER: Rpid neutron activation system (e.g. Cu activation with a 20min half-life) for extracting short lived nuclear isotopes activated by the NIF implosions as transient neutron source.
Interferometer / Polarimeter at 5w: Optical diagnostic for measure density profiles and magnetic fields in low density plasmas, relevant for discovery science and hohlraum science.

V-2: Local Diagnostic Development on Z

The development of new local diagnostic capabilities on Z is aimed at improving the fidelity by which we can measure time-dependent phenomena in all our HED platforms with an emphasis on the needs to understand stagnation dynamics in magnetic direct drive ICF. The majority of the development activities in FY18-19 are focused on x-ray diagnostics and transitions to more neutron diagnostic development in FY19-21 in anticipation of ~1% tritium operation on Z in FY20. Table 5 shows the present estimates of the timeline for development of the local diagnostics on Z. Here is a brief description of these capabilities and their applications:

CCPt: This is a convex crystal spectrometer coupled to an hCMOS camera in the axial diagnostic package. The primary application is time-gated opacity measurements.
TiGHER-PHC: This is a pinhole camera couple to a microchannel plate detector that is engineered to fit inside the Z target chamber for enhanced spatial resolution. The primary application is x-ray imaging of the stagnation in MDD-ICF.
Line VISAR: This is 1-D imaging open-beam VISAR system developed in collaboration between SNL and LLNL. The primary application is measuring current delivery to MDD-ICF targets.
HE-diodes: This is a high energy filtered diode array. The primary application is measuring the time-dependent x-ray output spectrum from >15 keV x-ray sources.

ODIN: This is a time-integrating, 1-D spatially resolving neutron imager. The primary application is neutron imaging of the stagnation in MDD-ICF.
CRS: This is a time-integrating spectrometer that measures recoil protons from DD or DT neutrons. The primary application is measuring the burn-averaged neutron spectrum from the stagnation in MDD-ICF.
Gated Backlighting: This is a spherical crystal backlighter coupled to an hCMOS camera. The primary application is measuring the liner mass distribution near stagnation in MDD-ICF.
Diagnostic Platform: This is a new diagnostic mounting platform in the Z target chamber that enables installation of pre-aligned target chamber diagnostics in one crane lift.
GRH: This is a gamma reaction history diagnostic to measure the time-history of the DT fusion production in MDD-ICF (requires ~1% tritium on Z).
DT-nImager: This is a time-integrating 2-D neutron imager optimized for primary DT neutrons from the stagnation in MDD-ICF.
MRS: This is a time-integrating spectrometer that measures the recoil protons from DT neutrons. The primary application is measuring the neutron spectrum from the stagnation in MDD-ICF with higher resolution and range than the CRSLocal Diagnostic Efforts on OMEGA



CCPt	Time-resolved Convex Crystal Spectrometer (hCMOS-enabled)
TiGHER-PHC	Time Gated High Energy Radiation Pinhole Camera
Line VISAR	Open Beam Imaging Velocity Interferometer System for Any Reflector
HE-diodes	High Energy Diode Array
ODIN	One-Dimensional Imager of Neutrons
CRS	Compact Recoil Spectrometer
Gated Backlighting	Time-Gated Spherical Crystal Backlighter (hCMOS-enabled)
Diagnostic Platform	Chamber Platform for Pre-Aligning Diagnostics
GRH	Gamma Reaction History
DT-NIS	DT Neutron Imaging System
MRS	Magnetic Recoil Spectrometer

Table 5: Estimated timelines for the local diagnostic effort on Z.

V-3: Local Diagnostic Effort on OMEGA

Diagnostic	Status	FY17–FY21 (Q1–Q4)
FBIT	CDR complete	Challenging (unique)
PXTD	CDR complete	New optics + ROSS
2nd LOS (nTOF)	CDR complete	Background/shielding
SLOS-TRIXI	Qualify FY17	On-track
Beamlets	First of 6 LOS in FY17	Duplicate (6) TIM-based instruments
PXRDP(t)	Prototype testing FY17	Formal diag requirements for FY18 start
Soft x-ray imaging	Prototype tested	Upgrade TIM-based pinhole cameras
3DnTOF	First arm operational	Duplicate first arm
TBD	FY18 start	Done before
EXAFSvH	FY18 start	New crystal
XANES	FY18 start	New crystal HiRes
3rd LOS (nTOF)	FY19 start	Few options
3rd LOS GXI	FY18 start	Technology choice
High Res Spec - OMEGA	FY18 start	Based on EP version
GXSC (2x)	FY18 start	Existing Kentech tubes
NIF Scattered Light	CDR complete	Plan to add ~5x LOS per year
OTS-NIF	Ongoing until complete	LLE providing PAM, 5ω conversion testbed, amplifier design
		2020 review

FBIT: Full Beam In-Tank (UV intensity at TCC).
PXTD: Particle and X-ray Temporal Diagnostic (simultaneous proton, neutron and x-ray burn history).
2nd LOS (nTOF): New shielded nTOF line-of-sight (LOS) to make simultaneous DD/DT yield, Tion and ρR (via n, T backscatter plus new 10-12 MeV DSR) measurements; same capability and the OMEGA laCave nTOF.
SLOS-TRIXI: Single Line-of-Sight Time-Resolved X-ray Imager for hot spot imaging.
Beamlets: Gated Optic Imager to measure relative changes in OMEGA 60 plus the new TOP9 ("61st beam") refracted beam intensity to study detailed beam-to-beam CBET and polarization effects.
PXRDIP(t): Time-resolved diffraction (replace the image plate recording with an x-ray streak camera) to measure materials structure and phase changes at high pressure.
TBD: Transmitted Beam Diagnostic (measures the energy of the TOP9 ("61st) beam through the target (typically a gas jet).
EXAFSvH: New crystals in existing von Hamos spectrometer for Extended X-ray Absorption Fine Structure measurements of various materials.
XANES: New crystal(s) in EP High Resolution Spectrometer to measure X-ray Absorption Near Edge Structure modulations.
3rd LOS (nTOF): Third shielded nTOF LOS for measurements similar to the 2nd LOS; this would provide roughly 4π neutron spectral coverage to compare with 3D hydro simulations.
3rd LOS GXI: A third line-of-sight for a gated x-ray imager for hot-spot imaging (likely to be a duplicate of either the existing 16-channel framed KB imager or a variant on the single line-of-sight time-resolved x-ray imager, SLOS-TRIXI, being installed on OMEGA for measurements in Q4FY17).
High Res Spec – OMEGA: A near duplicate of the EP high resolution spectrometer with relaxed shielding requirements for hard x-rays and more crystal options.

GXSC: "Generic" X-ray Streak Camera that will use existing streak tubes and pulsers, packaged for use in a TIM with added configuration options beyond the Static Streak Camera version A.
NIF Scattered Light: New compact instrument for spectroscopic SBS and SRS measurements; likely fiber based (LLE prototype underway).
OTS-NIF: Optical Thomson Scattering (5ω) for LDD on the NIF (LLE working with NIF on technology and requirements).

Appendix A: NNSA Memo "Establishment of the National Diagnostic Working Group as a standing coordinating committee for identifying and prioritizing transformative diagnostics for the ICF Program" 11/3/17

Department of Energy
National Nuclear Security Administration
Washington, DC 20585

November 3, 2016

MEMORANDUM FOR ICF EXECUTIVES

FROM: NJEMA J. FRAZIER
ACTING DIRECTOR
FOR INERTIAL CONFINEMENT FUSION

SUBJECT: Establishment of the National Diagnostics Working Group as a standing coordinating committee for identifying and prioritizing transformative diagnostics for the ICF Program

Summary: It is the assessment of NA-112 that a National Diagnostic Working Group (NDWG) is necessary for identifying and prioritizing the development of transformative diagnostics for all National Nuclear Security Administration (NNSA) High Energy Density (HED) facilities. By fostering regular communication and coordinating activities between the laboratories and various academic and industry partners, the NDWG will safeguard against a duplication of effort, and serve to define the frontier of diagnostic development. Additionally, the leadership and input provided by the NDWG is necessary to ensure that the National Diagnostic Plan (NDP) remains a valuable resource for NNSA program planning.

Background: The NDWG has been operating since 2009 in furtherance of the development of advanced diagnostics for the Inertial Confinement Fusion (ICF) Program, as an informal organization of technical experts. It has participation from 17 institutions including all three NNSA laboratories, foreign partners, private companies, and leading national technical universities. The group has focused on the development and fielding of diagnostics to support national missions for NNSA's HED experimental facilities: the National Ignition Facility, Z, and Omega/Omega EP.

In response to a 2014 request from the Senate Energy and Water Development Subcommittee, this group developed a multi-year NDP that was highly praised by an independent panel of experts, commissioned by NNSA, who reviewed the plan in January 2015. NNSA has committed to support the plan to provide transformative diagnostics for their HED facilities in the Fiscal Year 2017 President's Budget Request. As further evidence of the importance and prominence of this work, NNSA Defense Programs (DP) selected development of transformative diagnostics for the 2017 "Getting the job done" list, recognizing that the inherent multi-site and multi-facility nature of this effort is the key to increasing the scientific understanding of Stockpile Stewardship on the NNSA facilities.

Organization & Leadership:

The NDWG will consist of broad representation from the diagnostics community, nationally and internationally, including experts from NNSA's principal HED facilities,

Printed with soy ink on recycled paper

Appendix B

Summary of the National Diagnostic Working Group (NDWG) Meeting

LLNL, November 29-30, 2016

On November 29th and 30th , 2016 the NDWG met for the eleventh time with 115 invited participants from LLNL, LANL, SNL, LLE, NSTec, GA, AWE, CEA, Universities, and Industry.

LLNL	46
SNL	15
LANL	14
LLE	9
GA	4
CEA	4
MIT	2
NNSA	2
NSTec	2
Sydor	2
AWE	2
IC	1
Kentech	1
NRL	1
UNR	1
Prism	1


National Diagnostic Working Group
LLNL, November, 2016

Over the course of several meetings, an NDWG leadership group has identified many areas where a national collaboration on diagnostics for the ICF HED facilities has been beneficial and could be effectively expanded. Two categories of efforts have been identified that require national coordination: (1) eight new transformational diagnostics and (2) "broad" diagnostics using already developed techniques but requiring further common developments.

Some of the eight transformational diagnostics have detailed engineering plans which were presented in plenary sessions. These were:

Plenary Presentation	**Speaker**	**Institution**
Status of Optical Thomson Scattering	George Swadling	LLNL
Status of hCMOS Digital Framing Cameras	John Porter	SNL
Status of Neutron/Gamma Imaging	Petr Volegov	LANL
Status of High Resolution X-ray Spectrometers	Phil Nilson	LLE

However, most of the work of the meeting was done in a set of eleven breakout groups during three parallel sessions. These were set up with directed scientific discussions to address specific questions posed by the NDWG leadership needed to update the National Diagnostic Plan and recommend important areas of collaboration and investment to the NNSA and Laboratory leaderships. The eleven breakout sessions with chairs and discussion leads were:

Breakout Session	Chair	Discussion leads
1.1 Precision nToF	A. Moore	Hahn, Forrest, Sayre
1.2 Mix and Te	S. Regan	Harding, Ma, Thorn, Chen, Hall
1.3 Pulse Dilation	T. Hilsabeck	Meadowcroft/MacPhee, Hares/H. Herrmann, Engelhorn
2.1 Image Analysis	J. Field	Field, Volegov, Ampleford
2.2 Hard X-Ray Detectors	P. Bell	Wang, Opachich, Looker, Porter
2.3 MRS (time)	J. Frenje	Parker, Hilsabeck
2.4 XDV	J. Koch	Koch, Harding, Higginson
3.1 Phase Change (t)	R. Benedetti	Boehly, Jenei, Ao
3.2 n/gamma Imaging	G. Grim	Hibbard, Wilde, Fittinghoff
3.3 Synthetic Data	P. Knapp	Springer, Golovkin, Appelbe, Michel
3.4 Reflective Imaging	L. Pickworth	Kozioziemski, Troussel, Soufli

Summaries of the eleven breakout group discussions with answers to questions and recommendations follow.

<u>Session 1.1: Precision Neutron Time of Flight (nToF)- A. Moore (LLNL)</u>

Measurement of the shape of the DT and DD neutron spectrum is key to evaluating the performance of ICF implosions. The width of the spectrum characterizes the implosion ion temperature, while the number of down-scattered (DSR) neutrons is proportional to the fuel ρ-r or compression. Recent analytical work has also shown that much more information (such as the bulk flow velocity and range of burn temperatures) can be inferred from the shape of the neutron spectrum if it can be measured to high precision.

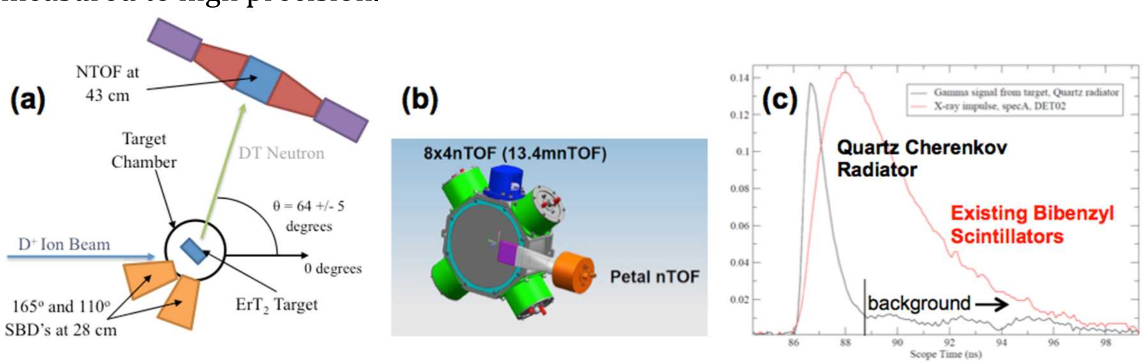


Figure 2. (a) SNL Ion Beam Laboratory neutron IRF measurement, (b) Omega nToF detector with new Petal nToF, (c) NIF nToF IRF width improvement with new Quartz Cherenkov Radiator

The current nToF technology used at NIF, Z and Omega is a neutron scintillator (that converts neutrons to photons) combined with a photo-multiplier photon detector. Each facility uses different variations of this technology, which has the main limitation that at the distance from the implosion that a detector can be practically fielded (~10-25m), the instrument response function (IRF) width is a significant fraction of the neutron spectrum width. Consequently the IRF must be extremely well understood to interpret the spectral shape. To complicate this issue, measurement of an in-situ neutron IRF is not possible so all facilities opt to measure the x-ray induced IRF and assume it is the same. Further, the limited shot availability severely limits the available statistics of in-situ IRF measurements, leading to relatively high uncertainty and low dynamic range. Finally, the scattering environment must also be accounted for via monte-carlo simulation and incorporated into the IRF. At Z in particular the scattering environment is very challenging, and so must either be understood to a high confidence or mitigated with expensive shielding.

Kelly Hahn from SNL discussed recent updates to the nToF detectors at Z and a new capability they have developed to measure the neutron-induced IRF using Sandia's Ion Beam Laboratory via coincidence measurements – Fig 1(a). Chad Forrest from LLE reported on a second collimated line-of-sight that is being developed on the Omega facility and new on- and offline x-ray IRF measurements to monitor the aging of their xylene scintillator – Fig 1. (b). Daniel Sayre from LLNL presented some new results from NIF that replaces the current scintillator with a quartz Cherenkov radiator. This results in a five times reduction in the width of the IRF which should significantly decrease the uncertainty in the ion temperature measurement – Fig 1. (c).

Questions posed by the NDWG:

Is more collaboration warranted for determination of the constituent and integrated IRF?

The group consensus was that despite quite different yield conditions at the facilities there was a benefit to a cross-lab effort on IRF determination. Progress has been made at individual labs to develop local facilities to characterize scintillators and detectors (MTW, COMET, 5w at LLNL, IBL). In particular a need was identified for access to a short-pulse x-ray source to address measurement of IRF to high precision.

Actions:

- Define a protocol/procedure for determining IRF
- Compare Optical, X-ray and Neutron excited scintillator IRF's

Is there hope for a faster epiphanous (n-to-light and light) detector for measurement of T_{ion}?

The recent Cherenkov detector offers potential for a significant reduction in IRF variance and, importantly, on-shot bang-time performance to determine the bulk velocity of the imploded fuel. Performance in the DSR region is yet to be evaluated.

The possible development of a fast plastic scintillator would eliminate current scintillator aging effects. There was also a general feeling was that there should be investment in capabilities to develop scintillators. A brief discussion of Neutron Counting options that don't suffer from the same IRF issues and have potential for high DR, indicated we should investigate leveraging recent hybrid-CMOS technology.
Actions:

- Evaluate if Cherenkov radiator could work at LLE and Z
- Propose LDRD for fast plastic scintillator
- Develop requirements for hCMOS based neutron counting detector

Session 1.2: Mix & T_e - S. P. Regan (LLE)

The participants of the Mix & T_e breakout session of the National Diagnostics Working Group Meeting were charged to address the following:

Compare and contrast the diagnostic signatures of mix (line, x-ray continuum/yield, thermonuclear fusion products)

The pros and cons of each mix diagnostic technique---tracer line emission, x-ray continuum/neutron yield, thermonuclear fusion products, monochromatic x-ray imaging, x-ray backlighting---were discussed. It was concluded that all of these techniques are needed to determine the source of the hot-spot mix and understand the impact of the hot-spot mix on the implosion performance. The mix signatures are sensitive to spatial gradients of the plasma conditions in the hot spot and the temporal evolution of the mix mass. The next generation of mix diagnostics needs to have spatial ($dx < 5\ \mu m$) and temporal resolution ($dt < 10$ ps) to understand the influence of these gradients on the measurements. A comparison of two mix diagnostic techniques on same implosion shot would provide helpful insight to evaluate the systematic errors.

Should there be a national collaboration on x-ray continuum slope measurements to infer hot-spot Te?

There was general consensus that a national collaboration on x-ray continuum slope measurements to infer T_e of the hot spot should be organized at the grassroots level to focus especially on the analysis and the interpretation of the measurements. P. Knapp, P. Patel, and S. Regan will organize the collaboration. As listed above, three diagnostic techniques were discussed to diagnose T_e of the hot spot based either x-ray continuum emission of line emission from a tracer element. Each of the three approaches will likely have a unique diagnostic design.

What diagnostics are planned/envisioned for each ICF approach to address mix and Te?

Magnetic Direct Drive:

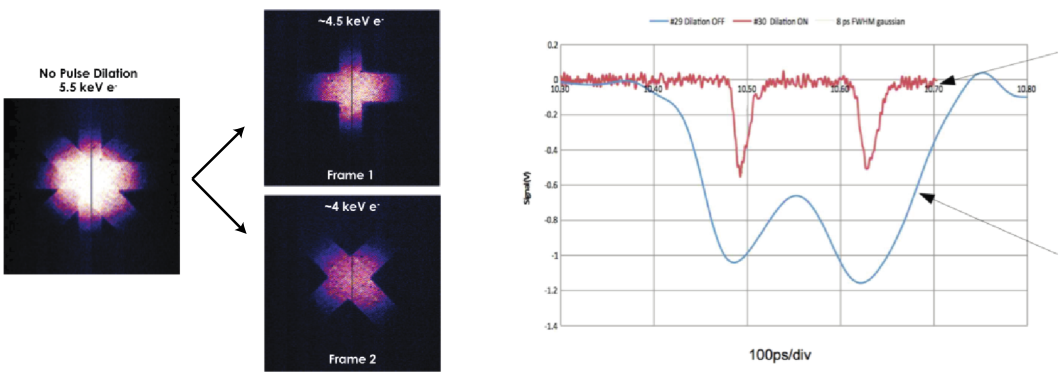
- Next generation spectrometer for Fe and Co line emission including hCMOS detector and Daedalus hCMOS detector with 1 ns temporal resolution
- Neutron imaging and filtered PCD's

Laser Direct Drive:

- 3-D (≥3 orthogonal lines of sight), time-resolved (dt<10 ps), absolutely calibrated hot-spot imaging (dx<5 μm) diagnostic inc[illegible]-2 for tracer and continuum emission
- Time (dt<10 ps) and space (initial: 1-D dx<hot spot; future: dx<5 m) resolved x-ray spectrometer for tracer elements (Si, S, Ti, Ge)
- Time (dt<10 ps) and space (initial: 1-D dx<hot spot; future: dx<5 μm) resolved x-ray spectrometer for x-ray continuum
- HT and DT gamma rays for mix measurements using separated reactants

Laser Indirect Drive:
- Higher spatial resolution (dx<5 μm) diagnostics to image small-scale mix features in hot spot using penumbral imaging
- 2-D monochromatic imaging to isolate high-Z mix line emission from x-ray continuum using the Crystal Backlighter Imager (CBI)
- X-ray spectroscopy – neutron-harden the time-resolved x-ray spectrometer (NXS) to run on high yield DT-layers; use differentially filtered SPIDER for time-resolved T_e and mix, and upgraded SPBT with 11, 22, and 33 keV channels for time-integrated T_e and mix)
- HT and DT gamma rays for mix measurements using separated reactants.

<u>Session 1.3: Pulse-dilation - T. Hilsabeck (GA)</u>



The Single Line-of-Sight X-ray Imager (SLOS) combines pulse-dilation with the nanosecond-gated, burst mode hybrid CMOS sensor to create a sub-nanosecond multi-frame x-ray imager. Results were presented from the prototype instrument showing two frame capture with 100 ps temporal spacing which was first tested in November 2016. The prototype is functioning as expected and the instrument build for the SLOS-TRXI LLE device is proceeding on schedule. The main discussions concerned the proper shaping of photocathode potential pulses and improvements to the hardware needed for operation in high yield environments. The Pulse-dilation Photomultiplier Tube (PD-PMT) prototype instrument results were also presented. This instrument is planned as an upgrade to the PMTs in the GCD diagnostic. The prototype demonstrations were successful and achieved a 10X improvement in temporal resolution. There is an anomalous behavior wherein the tube sensitivity at late times is reduced, but this may be due to contamination on the MCP and further tests are needed. Simulation results from a Pulse-dilation Streak Camera (PDISC) model were given along with a list of advantages and disadvantages of using pulse-dilation vs. conventional streak tubes. The pulse-dilation streak tube can achieve higher dynamic range due to the large photocathode area. However, this also requires a large area uniform wavefront from the source. Thus, the benefit of using a pulse-dilation streak tube will be application dependent.

Has testing at AWE and GA revealed issues such as intensity dropping unexpectedly with time?

Inconclusive. More testing needs to be done to calibrate the MCP back-end in the PD-PMT in order to answer this question.

Does full EM simulation reveal new insights or worries on dynamic range and resolution in the pulse-dilation streak camera?

Large area photocathode spreads out current density and so higher photocurrent can be launched before space charge degrades performance. Incident wave-front must be spatially uniform over this larger area.

What are the issues with getting the correct potential ramps onto the photocathode?

Photocathode potential ramps must be quite accurate to achieve uniform temporal magnification. It will be difficult to get proper ramp shapes without a programmable pulser. A radiation-hardened programmable pulser may be possible and a design will be considered.

Session 2.1: Image Analysis Breakout Session- J, Field (LLNL)

Three presentations were given by scientists from LLNL, LANL, and Sandia on instruments and techniques for x-ray imaging. Several important challenges and opportunities were identified and useful actions were recommended. Among the challenges cited were improvements to the spatial response of the GXD cameras at NIF, and the need for better metric definitions for the complex images we produce.

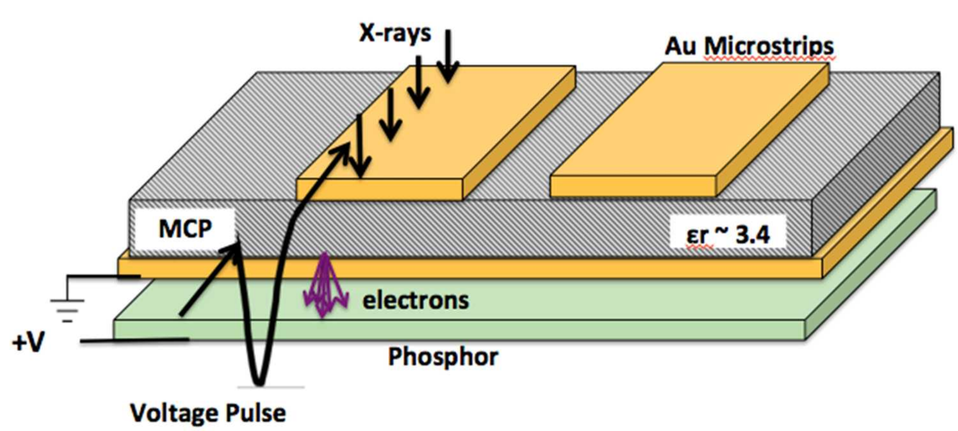


Figure 1: Schematic of the GXD detection plane. The phosphor image has a sizeable component of the detected light (~ 20%) in a very long spatial frequency tail.

What are the engineering improvements that could be made to the GXD cameras to eliminate the very long spatial tails?

1. Coat the backplane of the MCP with a low optical reflectance surface.
2. Sputtered Be on the MCP front face to increase conductivity and reduce droop.
3. Guard bands between the Au strips to reduce cross coupling.
4. Develop a detailed analytic droop model.
5. Tapered Au microstrips to use impedance change to compensate droop.
6. Aluminized phosphors to eliminate reflections (optical and electron).

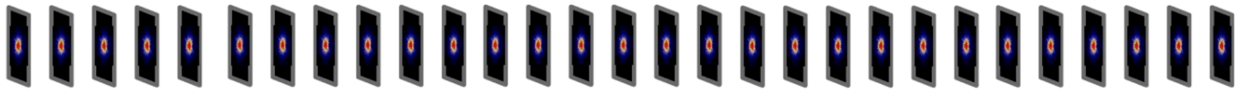
What can we do to improve metric definitions for our complex images?

1. Moment based methods have proven to be more robust when applied to synthetic images than surface based metrics.
2. There is broad interest both on the simulation and on the experiment side to push forward Bayesian methods which propagate the entire uncertainty distribution of the measured quantities instead of just the error bars. To be effective, this requires good characterization of the detectors (and therefore relates to the previous question).
3. Petr Volegov of LANL described the impressive progress his team has made in characterizing the fuel assembly at stagnation using Expectation-Maximization (GEM) algorithms to process the raw neutron, x-ray, and gamma images from the diagnostics. There are currently imaging diagnostics in development at both NIF (Wolter and KB microscope) and Sandia Z-Machine (Wolter) which due to spatial non-stationary response function would benefit greatly from similar advanced image processing techniques, and the Volegov group is eager to collaborate.

Session 2.2: Detecting hard x-rays with < nsec resolution- P. Bell (LLNL)

X-Ray Detection with hν >20 keV is needed for many NNSA facilities. There are two main problems with hard x-ray detection (1)the absorption of materials drops requiring thick detectors which can be slow and (2) when an x-ray is absorbed many thousand secondary electron are produced reducing dynamic range in readout systems. High photon energy time resolved diagnostics will greatly enhance the ability of experiments.

Jeff Wang reviewed the August 2016 workshop on detectors for MaRIE. He explained the issues moving forward for X-ray Free Electron Lasers, like the Matter-Radiation Interactions in Extremes experimental facility (MaRIE) for high energy (30keV to 120keV) fast detection with a QE of >50% @ 42-120keV. The proposed research for such a system involves Application Specific Integrated Circuit (ASCI) devices with 3D hybridized diodes sensitive to harder x-rays. Past research in this area has shown fast optical (250 ps) ASICs can be produced. This ASIC technology requires further development to fill the need of this application.



Many images with low Qe can be added to give high Qe

<u>Question: Can transmission PCs be made better by morphology or materials? K Opachich</u>

Kathy Opachich spoke about her work on structured transmission photo cathodes. This is a collaboration started with Luxel and Space Science Labs to coat structured cathodes with Au, and other alkali halides. Kathy has coated full-scale structured cathodes with Au and has demonstrated a 3x gain in QE for transmission photo cathodes. Future work will include a demonstration with CsI and RbBr at higher X-ray photon energies. Promising progress has been made and we recommend this work continue.

<u>Question: What is the path forward with pixelated detectors and ROICs? Q Looker, J Porter</u>

Quinn Looker gave a talk on pixelated detector work he has been pursuing. His work on pixelated diodes that can be hybridized is making progress in materials selection and device fabrication. It is clear that GaAs is the material of choice today. With research, GaN could make for a better material. Quinn showed mitigation methods to reduce excessive charge that will be tested in the next few years.

John Porter and Perry Bell both spoke about low resolution (20 x 20) pixelated diode methods. John has focused his work on compact low cost digitization methods that can be pushed to 50ps sample times and 20ns record lengths. The work shown by Perry was from the 2002 timeframe of a diamond pixelated array that was built and tested, but never fielded.

There are two distinct paths forward for pixelated detector systems. One based on GaAs 3D hybridized ASICs with a time limit in the 200 ps range based on an array of ~500 x 500 pixels and the second, a GaAs low pixel count (40 x 40) array with 50ps sample times. Both methods have clear paths forward but are underfunded at this time to make progress quickly.

<u>Session 2.3: MRSt, time-resolved measurements of the neutron spectrum- J Frenje (MIT)</u>

The Magnetic Recoil Spectrometer (MRSt) for time-resolved measurements of the neutron spectrum (see figure below) represents a paradigm shift in the thinking about neutron spectrometry for ICF applications, as it will simultaneously provide information about the burn history and time evolution of areal density (ρR), apparent ion temperature (T_i), yield (Y_n) and macroscopic flows during burn. From this type of data, an assessment of the evolution of the fuel assembly, hotspot and alpha heating can be made.

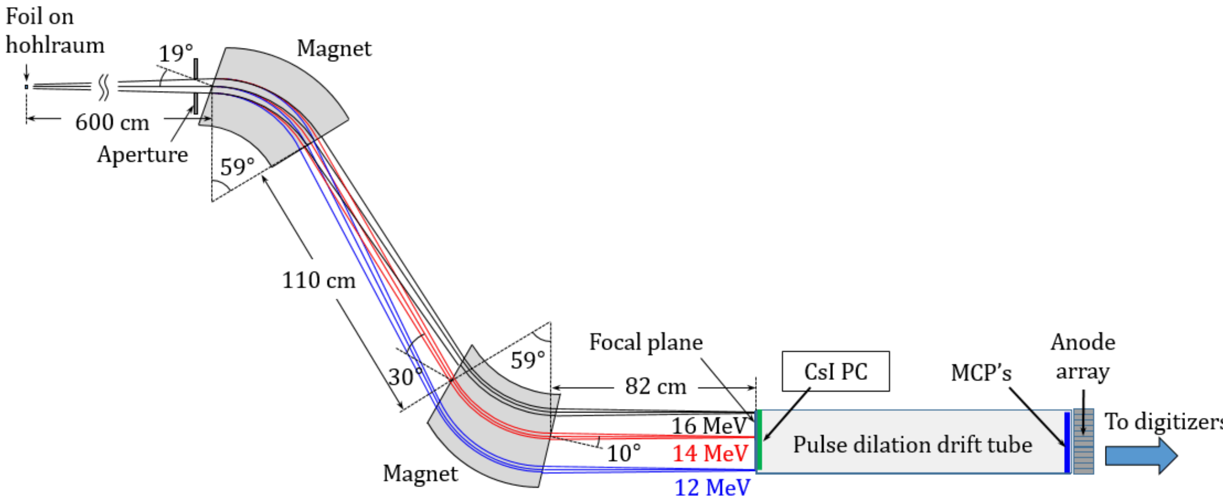


Figure 1: Schematic of the MRSt main components. Shielding will fully surround MRSt.

<u>What are the critical tests that need to be made to go forward with MRSt as an engineering project?</u>

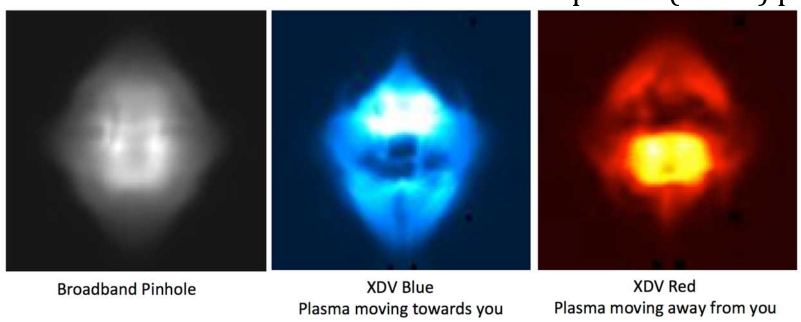
Frenje led the MRSt break-out session that focused entirely on addressing this question. The outcome of this discussion is that four experimental tests must be completed before the MRSt project can go into an engineering phase:

1. Test the characteristics of the foil on a hohlraum using an experiment at the NIF. This test is required to understand the MRSt efficiency and energy resolution, which are dictated by the area and areal density of the foil. The plan is to use a 500-μm diameter, 40 μm-thick CH_2 foil positioned on the holhraum and a WRF proton spectrometer for this test (aim for an experimental test in FY17 Q4).
2. Test the CsI PC response (sensitivity/pulse-height spectrum) to various ions with different energies using the MIT-HEDP accelerator (tests scheduled for FY17 Q2). Understanding the CsI PC response to ions is essential for the optimization of the MRSt signal-to-background (S/B) (scheduled for FY17 Q2).
3. Test the MRSt deskew/pulse-dilation concept. Hilsabeck at GA has demonstrated that the MRSt signal deskew/dilation concept can be done in principle, but the question is if a mechanical design of micro-strip line structure and CsI converter, and the back-end read-out system, including MCP's and several anode channels with digitizers can be built according to specifications (demonstration by the end of FY18 Q1).
4. Test the MCP response to electrons (signal) and neutrons (background) using OMEGA and the MIT-HEDP electron and neutron sources. These tests are

strongly connected to test #2 in our efforts understanding the MRSt S/B (scheduled for FY17 Q3).

Session 2.4: X-ray Doppler Velocimetry (XDV) – J. Koch (NSTec)

XDV is a NNSS-led concept for diagnosing fluid flow velocities and residual kinetic energy in ICF implosions, using multi-spectral x-ray imaging. It is currently supported as a NNSS site-directed research and development (SDRD) project.



Jeff Koch described progress to date on developing the XDV concept. Most of this work has been computational simulated image development and analysis proving the basic concept. The main conclusion was that by all efforts to date, the concept is sound and would be expected to generate exciting data on fluid motion in a NIF implosion hot spot. Eric Harding described an existing two-crystal imaging system that has been fielded at Z, and discussed several possible development experiments for XDV. Higginson described experiments at Omega and NIF, looking for collisionless shocks in colliding plasma experiments. Discussion centered on what could be done using this platform to prove the XDV concept. Roberto Mancini described a methodology that could be applied to XDV image data analysis. This involves the use of genetic algorithm search and reconstruction techniques to find an optimum physics model for the object being viewed that best matches available data.

<u>What is next on Z for multi-spectral imaging?</u>

The main issues for XDV experiments at Z are, selecting an appropriate experiment that is already on the shot schedule, procuring and calibrating appropriate crystals, and revisiting the alignment technique to ensure that it is precise enough for XDV. An action was to explore the prospects for ZBL-only experiments, which have many advantages over Z implosions if they are suitable for XDV development. Infrastructure already exists, and ZBL experiments are easier to schedule and do not destroy hardware.

<u>What needs to be done to prepare for an Omega XDV series?</u>

Fielding experiments at Omega remains a possibility, but modifying the existing single-crystal, dual-opposed-TIM imager for two crystal imaging would be challenging and might not be practical. More work by Omega staff is required to explore this option. Such a system would also be restricted to the T4/T6 axis.

Should there be a planar interpenetrating XDV development platform?

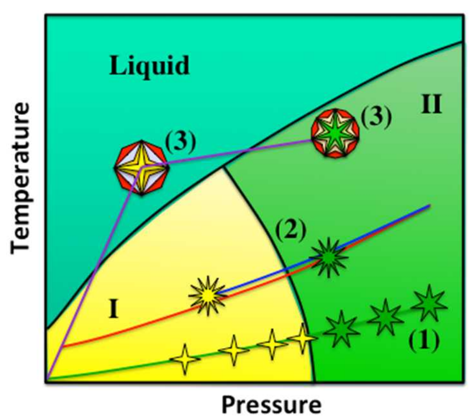
At a minimum, 2D simulations of the velocity fields need to be examined in order to determine what sort of spatial structure might be observed, before we can answer this question. These simulations may already exist, and an action was to find and distribute them to the group.

How will we quantitatively analyze XDV data?

Analysis of XDV data will be challenging, but it appears that the general methodology developed for Omega implosions will be applicable to XDV images as well. An action was to explore a simple rotating-ball plasma physics model in order to develop the computational techniques, without reliance on hydrodynamics simulations.

Session 3.1: X-ray Diffraction for Time-Dependent Phase Changes- R. Benedetti (LLNL)

X-ray diffraction (XRD) is the only unambiguous method to document a phase transition during dynamic compression, and it is consequently a critical tool to support materials science experiments at the HEDP facilities. Examining the process of transformation may be as scientifically rich as phase diagram determination itself. Indeed, determining the rate-limiting processes during pressure-driven transitions was identified as a grand challenge at a recent multi-lab kinetics workshop. Further, it may be possible to design and recover new materials by harnessing phase transition kinetics.



Pathways through phase transitions that can be examined dynamically: (1) Compression through a phase transition. (2) Hysteresis in release transformations. (3) Shock melting and ramp compression into a solid phase

Since last year's NDWG meeting, the labs have demonstrated substantial progress toward design of experimental platforms for time-resolved XRD. LLE and NIF are working in collaboration because of the similarity in facility and timescale requirements. In contrast, the longer timescale and harsh environments at Z lead to a substantially different conceptual design with fewer obvious areas for synergistic overlap. Still, we found that while the specifics are different, the challenges are largely similar.

Tommy Ao and Marius Schollmeier (SNL) presented the status of the XRD platform at Z. The preliminary design uses the Z-Beamlet laser to produce a plasma x-ray source and collects diffraction by a scintillator optically relayed to a gated CCD. A demonstration experiment is scheduled for Aug., 2017. Methods to improve temporal performance were also described.

Amy Jenei (LLNL) described the progress the HED shock physics group at LLNL has made documenting phase transformations and their kinetics utilizing several experimental techniques. This discussion provided important context for the role of the HED facilities relative to other user facilities.

Laura Robin Benedetti (LLNL) described the progress and challenges in developing time-resolved diffraction at NIF and OMEGA. At NIF, a concept for time-resolved XRD is being developed that builds on the success of the TARDIS platform. Streaked data along one line of sight will be combined with multi-frame imaging (to evaluate preferred orientation and texturing) along two additional lines of sight. Collection of a continuous record of XRD throughout a transition (via streak camera) is an important capability that will continue to differentiate the large lasers from synchrotron and free-electron laser x-ray sources.

<u>What is the best goal for the next phase change measurements for HEDP facilities?</u>

Both Z and the Omega/NIF teams have identified an initial experiment to perform that uses mature technologies in order to have a high probability of success. Based on the results of the initial experiment, physics performance will be improved using more exotic techniques.

<u>What are the practical issues for progress on Z, NIF and OMEGA?</u>

The following issues are important and relevant to all of the XRD platforms under development:

a) x-ray sources that meet intensity and temporal requirements;
b) sufficient photometrics to collect high quality data; and
c) developments in multi-frame hCMOS detectors (SNL).

Session 3.2: Neutron/Gamma Imaging Breakout Session - G. Grim (LLNL)

The n/γ imaging breakout session looked at the near term path forward for nuclear imaging on the NIF. The options are:

1) reconfigure the equatorial neutron imager (NI-EQ315) to provide dedicated gamma imaging,
2) implement energy gated neutron imaging (NI) on the north-pole neutron imaging (NI-NP) line-of-sight (LoS),
3) begin design of a 3rd neutron imaging LoS on the equator, or
4) a combination of scope from these options.

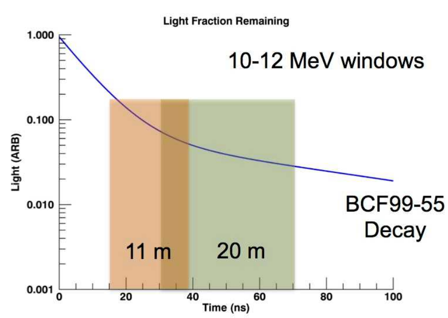
Figure 3.2a: NI-EQ315 Scintillator decay curve.

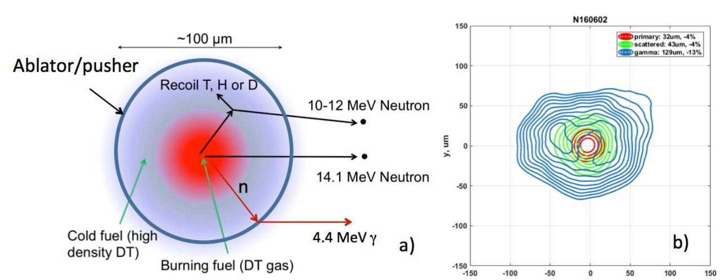
Figure 3.2b: Comparison of expected neutron to gamma images.

Questions posed:

1. What should we do next on the NIF?
2. What are the prospects for better detectors to reduce engineering costs of n/γ imaging?

Hibbard presented a summary of facility costs associated with locating detectors inside and outside the NIF facility. It was concluded that new diagnostics should remain within the Target Bay if possible and should not be located outside the building. For option 2) this imposes the requirement for a fast decay scintillator and significant shielding of the gated camera. Fittinghoff summarized a concept to address camera shielding, by presenting the design of the NI system implemented at 1 m on the Z-facility. In Fig. 3.2a, Grim showed that inside the Target Bay, the residual light produced in the current NI scintillator from primary neutrons is ~4X that produced by scattered neutrons for a detector located at 11 m. The ratio of light produced from down-scattered neutrons to primary neutrons must be greater than 1, but on NI-EQ315 it is estimated to be ~0.25 with present scintillators. No scintillator was presented that can meet this requirement. Thus, a study is needed to identify if there is an appropriate scintillator and imaging configuration that will enable energy/time gated imaging on NI-NP. In Fig. 3.2b, Wilde illustrated the benefits of gamma imaging from a scoping exercise at the NIF. The red contours show the size and shape of the fusion neutrons, the green the scattered neutrons, and the blue the imaged gammas collected by NI-EQ315. *This full image of the compressed assembly provides useful inputs for post-shot modeling, as well as a stringent challenge for validating predictive capability.* Implementing gamma imaging on NI-EQ315 is a low-risk, engineering project that augments the existing





camera hardware with a dedicated gamma imaging station and a new aperture to meet requirements of sensitivity, resolution, and co-registration. Design of a 3rd NI imaging LoS in the equatorial plane is also a low-risk and straightforward engineering project. Thus, the recommendation of the n/⍰ breakout group is for option 4), with the major technical elements of:

1. Investigate scintillators and identify a technical path forward on energy gated imaging along NI-NP by end of FY-17.

2. Implement a gamma imaging camera station and new gamma aperture on NI-EQ315 by mid-FY18.
3. Initiate a conceptual design effort for a 3rd primary neutron imaging LoS in the NIF equatorial plane with the goal of achieving a CDR by end of FY-17.

Session 3.3 : Synthetic Diagnostics - P Knapp (SNL)

Synthetic diagnostics are a critical part of our capability to design effective experiments and compare results to simulations. They involve processing of either integrated simulation or reduced model results to produce outputs as close as possible to those measured on experiments, ideally including realistic background and noise models. Accurate and efficient synthetic diagnostics are also critical for multi-objective data analysis, whereby data from multiple instruments are combined and analyzed simultaneously to infer parameters consistent with all inputs. This type of *advanced data analysis* attempts to integrate an entire dataset, typically through a model, as opposed to the traditional approach of analyzing different data serially.

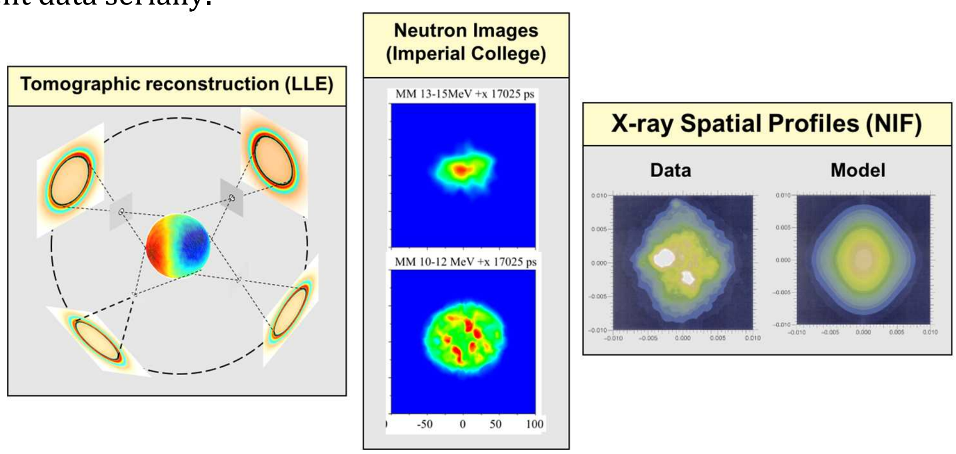


Figure 3.3a: Examples of synthetic data produced from simulations and models from LLE (left), Imperial College (center), and NIF (right)

Synthetic diagnostics span the entire space of instruments available, from optical, x-ray, nuclear, electromagnetic and others. Some are simple and amenable to post-processing of simulations. Others, e.g. some nuclear and x-ray diagnostics, are computationally very expensive and are most accurate when computed inline with the simulation. Nuclear diagnostics involving events with low probability (e.g. RIF's) struggle to achieve statistics necessary to overcome noise in practical calculations. X-ray diagnostics, particularly spectroscopic ones, require high fidelity atomic models and radiation transport, making them expensive. Additionally, the issues of background and noise are important considerations when designing new experiments or diagnostics.

The subject of multi-objective data analysis is somewhat new in the field of HEDP and ICF. Pioneering work by Mancini *et al.* has demonstrated the utility of this approach using a Pareto Genetic Algorithm applied to x-ray spectroscopic data. We identified three approaches to this problem that are being either actively used or explored: Pareto Genetic Algorithm, Chi-squared minimization, and Bayesian inference. The first two methods are the most mature, with a Chi-squared minimization across multiple types of data in use at LLNL for several years now. LLNL and SNL are independently investigating the use of Bayesian inference applied to this problem. All of these approaches require a model which is able to approximate the hot spot at stagnation and generate the appropriate synthetic data. The model, in principle, can be swapped out, allowing for quantitative comparison of different approximations with the data. This approach, known as *model selection*, is well established and quantitative metrics have been developed.

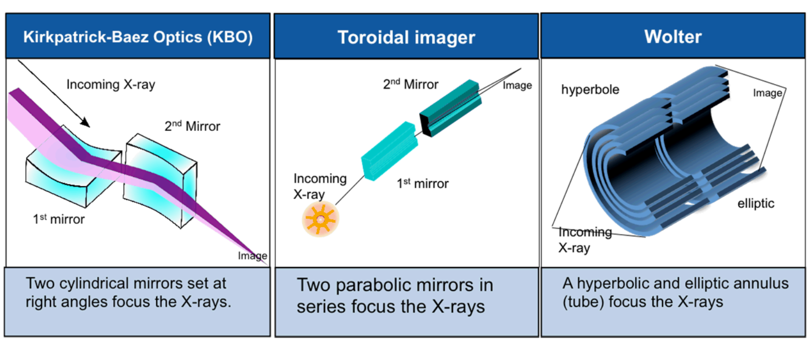
<u>What is the path forward for synthetic diagnostics?</u>

The need was identified for diagnostic models to be compared and shared among sites. This is particularly important for the computationally expensive diagnostics where varying assumptions and simplifications are used by different people. Where "standard" diagnostics exist at different facilities, a common synthetic diagnostic should be developed to aid in collaboration and comparison between codes/facilities. Background models must be investigated for a variety of measurement types and across different facilities.

<u>What is the path forward for multi-objective data analysis?</u>

It was suggested that a mini-workshop be held, as early as the summer of 2017, focused on multi-objective data analysis. We suggest bringing together a *small* group (~2-3 people from each lab working on the analysis) to discuss the different approaches being taken, the specific implementations and plans for the future. Plans to conduct head-to-head comparisons and sharing of tools should be an outcome of this workshop.

<u>Session 3.4: Reflective X-ray Optics – L. A. Pickworth (LLNL)</u>



Reflective x-ray optics systems have been developed as a means of improving 2D time resolved x-ray imaging of HED plasmas. These systems use grazing incidence x-ray mirrors to form an image. NIF and Omega currently have multi-channel Kirkpatrick-Baez (KBO) microscopes that provide ~5 μm spatial resolution with improved signal at the detector over comparable pinhole imaging systems.

Reflective x-ray optics promise good resolution (<5μm) tunable photon energy response through multilayer x-ray mirrors and large collecting solid angles required for hard x-ray imaging >15 keV. Two systems were discussed in this session: The toroidal optic, developed at CEA, and the Wolter optic both offering larger collection than a KBO system.

What are the prospects for future Wolters on Z?

Z will have a functioning Wolter for Mo K-alpha imaging by FY18. Imaging on Z requires a large field of view (~20mm) with 100 μm resolution. Success, and future optics, depends on meeting this requirement with a 'narrow energy band' mirror coating.

Where could toroidal x-ray microscopes fit in (on NIF)?

Initial scoping of a multichannel design that may be compatible with NIF promises <5 μm resolution over a 800 μm field of view, with a 5x increase in solid angle over the NIF KBO design. This meets the initial requirements for hotspot self-emission imaging at <20keV. A collaboration with CEA is developing.

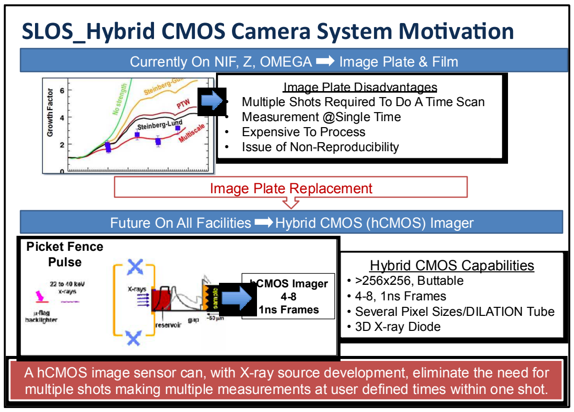
Challenges of multi-layer coatings for large solid angle reflective imaging?

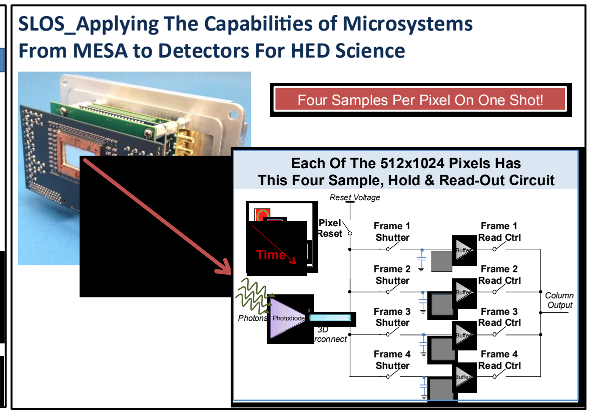
Design of multilayer mirrors is made challenging by the large acceptance angles needed to have reasonable fields of view. To maintain good illumination over the field the d-spacing required becomes complex, this is more challenging for >15 keV. Future optics will benefit from further investment in multilayer & material expertise at LLNL.

Next steps for reflective implosion imaging on NIF, OMEGA and Z?

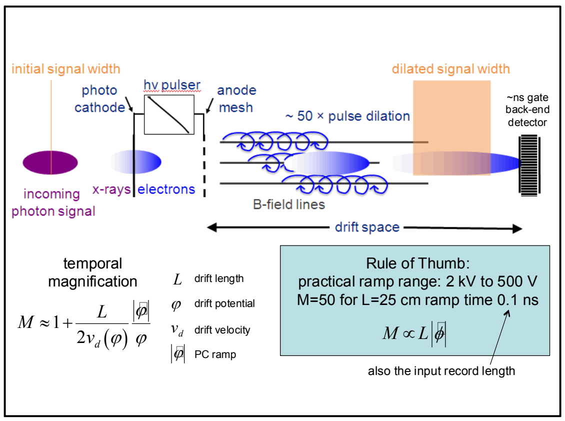
The toroidal optic provides a natural "next step" from the KBO imager on NIF. Replicated Wolter technology cannot yet meet the NIF requirement of 5 μm resolution. We have started work with NASA-Marshall to improve the resolution. If we can meet the resolution requirements for NIF there is a path to time-resolved imaging of the self-emission from an ICF hotspot at ~30 keV.

Appendix C- Principle of Operation of Transformational Diagnostics

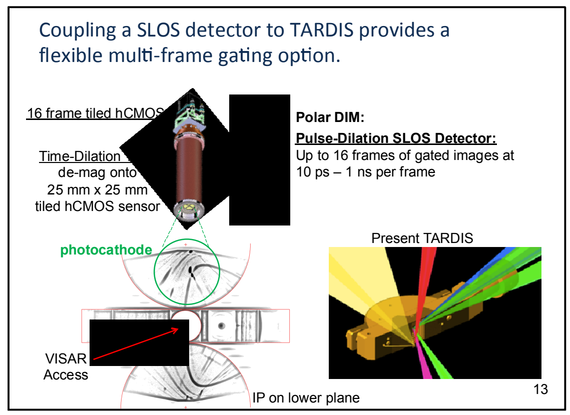




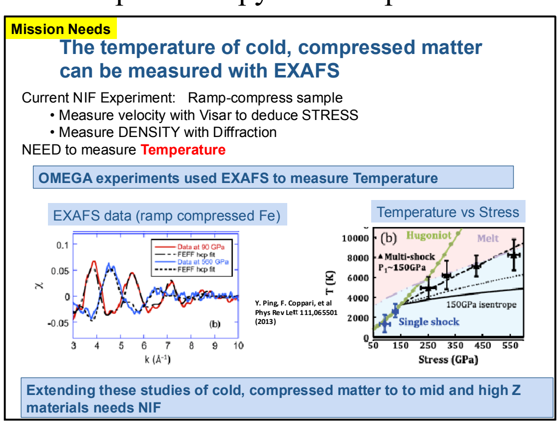
DIXI –Time dilation



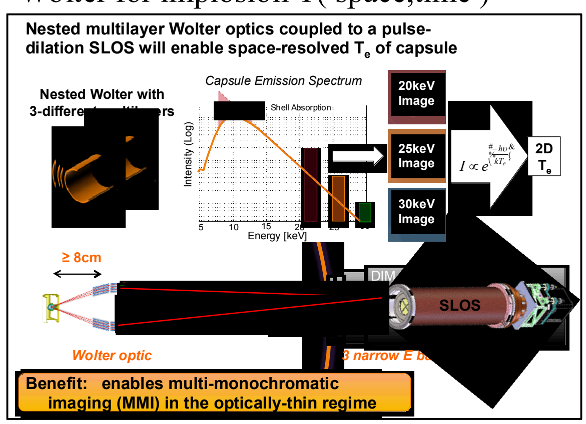
Time resolved Diffraction



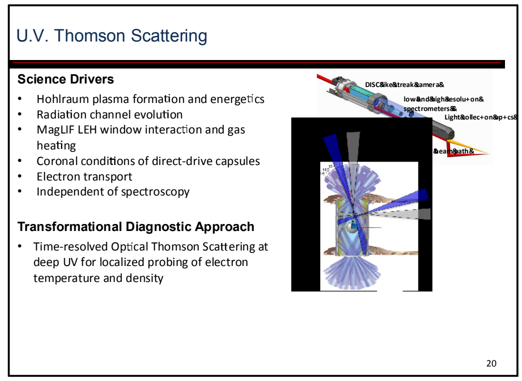
HI Res Spectroscopy for Compressed Pu



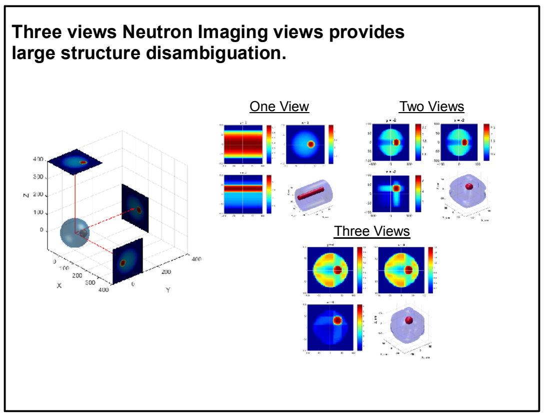
Wolter for implosion T(space,time)

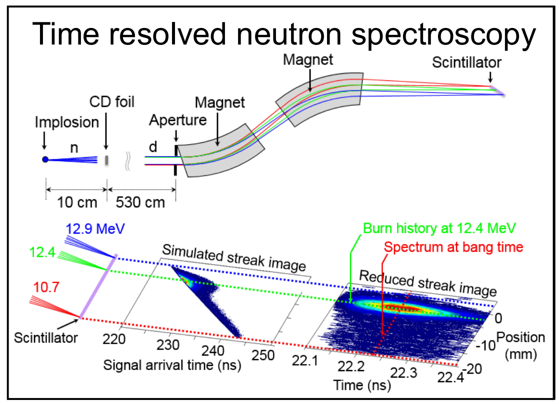



Enhanced Gas Cherenkov Detectors for Reaction and ρR$_{Abl}$ Histories
Super GCD:
• High Sensitivity (~200xGRH-6m)
• High Temporal Resolution (10 ps goal, ~10x faster than GRH-6m)


U.V. Thomson Scattering
Science Drivers
• Hohlraum plasma formation and energetics
• Radiation channel evolution
• MagLIF LEH window interaction and gas heating
• Coronal conditions of direct-drive capsules
• Electron transport
• Independent of spectroscopy
Transformational Diagnostic Approach
• Time-resolved Optical Thomson Scattering at deep UV for localized probing of electron temperature and density
20

ß


Three views Neutron Imaging views provides large structure disambiguation.
One View
Two Views
Three Views


Time resolved neutron spectroscopy
Magnet
Scintillator
CD foil
Magnet
Implosion
Aperture
n
d
10 cm
530 cm
12.9 MeV
12.4
10.7
Scintillator
Simulated streak image
Burn history at 12.4 MeV
Spectrum at bang time
Reduced streak image
220
230
240
250
Signal arrival time (ns)
22.1
22.2
22.3
22.4
Time (ns)
0
-10
-20
Position (mm)