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I. Introduction

A team headed by LANL and including many members from LLNL and NSTec LO and NSTec LAO fielded a neutron imaging system (NIS) at the National Ignition Facility at the start of 2011. The NIS consists of a pinhole array that is located 32.5 cm from the source and that creates an image of the source in a segmented scintillator 28 m from the source. The scintillator is viewed by two gated, optical imaging systems: one that is fiber coupled, and one that is lens coupled. While there are a number of other pieces to the system related to pinhole alignment, collimation, shielding and data acquisition, those pieces are discussed elsewhere and are not relevant here. The system is operational and has successfully obtained data on more that ten imaging shots.

This remainder of this whitepaper is divided in five main sections. In Section II, we identify three critical areas of improvement that we believe should be pursued to improve the performance of the system for future experiments: spatial resolution, temporal response and signal-to-noise ratio. In Section III, we discuss technologies that could be used to improve these critical performance areas. In Section IV, we describe a path to evolve the current system to achieve improved performance with minimal impact on the ability of the system to operate on shots. In Section V, we discuss the abilities, scope and timescales of the current teams and the Commissariat à l'énergie atomique (CEA). In Section VI, we summarize and make specific recommendations for collaboration on improvements to the NIS.

II. Improvement Drivers for the NIF NIS

The present NIS was designed to provide the proper data input for the National Ignition Campaign (NIC) by balancing a number of different design requirements[1] based on implosion simulations[2]—such as high resolution and low signal-to-noise at specific image contours—for imaging both primary and down-scattered neutrons for primary neutron yields between 5x10^{15} and 1x10^{19}.

Since the current primary yield record at NIF is only 6.9x10^{14}, all shots taken so far have been well below the design yield, and performance improvements are expected to occur as the yield rises. Based, however, on the initial calibrations of the system and performance of the system, we have identified three main areas of concern that will likely drive design changes for the current system: spatial resolution, scintillator temporal response and signal-to-noise ratio.

a. Spatial Resolution

Based on our simulations, the resolution of the NIS system in its current configuration is predicted to be ~22 μm. Part of this is due to our current use of the NIF #1 Pinhole Array, which has three mini-penumbral pinholes and 20 single-sided triangular pinholes, with its front surface at 32.5 cm from target chamber center (TCC). Since 32.5 cm is not the design position of 22.5 cm, moving the pinhole to its design position would increase the magnification and hence the resolution of the system. Additional improvement is possible by switching to the NIF #2 Pinhole, which has square pinholes that are effectively smaller because they taper from the ends to an apex inside the pinhole body. Unfortunately, these improvements will not reach the system design requirement for a minimum spatial resolution of 10 microns or better at the target plane.

The major limitation to the spatial resolution is the current scintillator design. The scintillator that is currently being used is a 160-mm x 160-mm x 50-mm thick array of 250-μm round BCF-99-55 scintillating fibers purchased from Saint Gobain. While similar arrays have been used before[3], the spatial coherence of these scintillators is not perfect and the inherent resolution in the scintillator is poor. For a perfectly manufactured scintillator array, the expected line-spread function for DT neutrons is ~ 0.7 mm [1]. In recent measurements at NIF using a rolled edge to measure primary neutrons, the edge spread function for the lens-coupled arm of the imager was ~1.24 mm, which translates to a resolution at the source of 15 μm at the current magnification. Since the resolution of the optical system for the lens-coupled imager has been measured to be 5.5 lp/mm for 50-ns gating, we believe that the poor resolution is due to the scintillator and not the optical system. This result is also consistent with a test of the scintillator at the NSTec LO Hex facility that showed an inherent resolution of the scintillator to x-rays of ~1.1 mm due to the poor spatial coherence of the scintillator.

To achieve the required 10-μm or better spatial resolution at the source, we will need either a scintillator array with significantly better spatial performance or a higher magnification imaging system combined with higher yields. Since the current 28-m long line of sight cannot be significantly lengthened without construction of a new line of sight and since moving the front of the pinhole array closer than 22.5 cm from the source would negatively impact the magnetic resonance spectrometer, violate the 20-cm stay out zone, require even greater shock resistance and reduce already small fields of view, we believe that obtaining a higher-resolution scintillator is the most reasonable method for achieving the desired resolution.

b. Temporal Response

On shot N110603-002-999 (IT_6_ExplPush_S26), the residual light ratio of the BCF-99-55 scintillator at the time of arrival of the down-scattered signal was measured to be 0.64% ± 0.2%, which is a signal that must be properly subtracted from the down-scattered images prior to reconstruction of the images. Reducing this light tail by using a scintillator with a faster long-time decay component would reduce any errors in this subtraction just as faster scintillator decays reduce the error in the down-scattered ratio from neutron time of flight (nTOF) measurements.

Additionally, the scintillator light is collected by two gated camera systems to produce images of neutrons in the energy bands from 13 MeV to 17 MeV and from 10 MeV to 12 MeV. The energy is determined by time-of-flight along the 2800 cm line-of-site and the accuracy of the scattered to prompt measurements is directly affected by the accuracy of the image gate timing. Current gating technologies used for these systems are based on mesh-grid, micro-channel plate image intensifiers, driven by high-voltage drive circuitry with rise times of ~10 ns. At 14.1 MeV, a 10 ns gate blur corresponds to ~500 KeV energy blur, greater than the specified 300 KeV resolution. Reducing the gate blur closer to 1 ns would allow the system to reach the required energy resolution.

c. Signal-to-Noise Ratio

The NIS requirements include measuring the imploded shape using Legendre Polynomial fits to obtain P0, P2 and P4. The relevant minimum signal-to-noise level of 10 is defined not at peak but at the 20±5% contour for the primary neutron image. The system is also required to have a signal-to-noise level of 22 at the peak intensity of the downscattered image. The use of penumbral and, in particular, ring-apertures to image neutrons have been shown to produce significant improvements in signal to noise for low-brightness neutron sources[4]. Imaging of weak signals, such as tertiary (a.k.a. reaction in flight) neutrons could benefit considerably from such methods.

III. Possible Technologies for Improving the NIS

a. Segmented Scintillator Arrays

To date, two scintillator technologies have been used could achieve the inherent resolution due to the energy deposition of the neutrons in the scintillator without additional new research: thin-slab scintillators and liquid-filled capillary arrays. There are also straightforward methods to improve the manufacture of fiber scintillator arrays that might allow them to achieve the inherent resolution of the neutrons in the material.

The major limitation to using a slab of a scintillator material is that the light generated is not guided to the surfaces of the slab. This means that the collection optics must have enough depth of field to collect light without degrading the image. The difficulty in designing the collection optic typically limits the thickness of the scintillator to less than a centimeter and potentially significantly less for uniform collection over large area scintillators, which in turn limits the neutron sensitivity. While such a system may become usable at very high yields, we do not consider it a viable option in the near term. Thus, we feel there are two scintillator technologies that should be pursued: glass capillary arrays and plastic fiber scintillator arrays.

Glass Capillary Arrays

The CEA has spent a number of years developing the technology to produce large arrays of 85-µm (current array is 65 µm) glass capillaries filled with liquid scintillator for neutron imaging. For 14-MeV neutrons, these scintillator arrays have 650-µm resolutions using non-deuterated scintillator and less than 400-µm resolutions using deuterated scintillators to reduce the recoil length of the protons produced when the neutrons interact with hydrogen[5]. Since this technology has been proven, a collaboration to add such a scintillator to the NIS line of sight would be a direct way to achieve the better than 10-µm resolution using the current pinhole arrays at the 22.5 cm from TCC.

Improving the spatial coherence of plastic optical fiber scintillator arrays

Producing a significantly more coherent array of scintillating optical fibers through better manufacturing methods or by making an additional draw of a sub-array is possible and worth pursuing since it would allow use of plastic as well as liquid scintillators. An NSTec suggestion, for example, to manufacture more sub-arrays than required for the final product and down-select for the best pieces would be a straightforward method to obtain better spatial resolution and should be pursued. At high yield, the expedient of simply slicing the current array in half might also prove effective but would be better pursued once higher yields are achieved.

b. Fast scintillator technologies

Several scintillators with faster long-time decay tails have already been identified by LLNL & LANL as possible nTOF scintillators. These include Liquid A [6-9] and crystal scintillators such as Bi-benzyl. At LLNL, work is also underway to produce similarly fast plastic scintillators based on polyvinyl- toluene (PVT) plastic. As shown in Figure 1, Bi-benzyl, Liquid A and one of the new plastic scintillators are all significantly faster than BCF-99-55. To date, most of these scintillators have been investigated for use for neutron time-of-flight measurements. For use in neutron imaging at NIF, we recommend investigating both fast liquid scintillators and fast plastic scintillators to be incorporated into segmented scintillator arrays.

Fast Segmented Scintillators Using Liquid Scintillators

For liquid scintillators, the difficulty to date is that none of the fast liquid scintillators, such as Liquid A ($\lambda_{\text{peak}} \approx 450$ nm), have an index of refraction that is high enough ($n \gtrsim 1.54$) for them to be used in glass capillaries. Thus a fast liquid scintillator will need to be produced with a higher index, or a lower index glass capillary array would need to be manufactured.

Attempting to produce capillary arrays from glasses with significantly lower index of refraction does not seem likely to succeed. Pure fused silica has $n \approx 1.465$ at 450 nm, and as impurities increase, the index typically increases. Moreover, precise manufacturing & machining methods used for the glass scintillators are also not expected to be directly transferable to pure fused silica, which has a higher melting point (~1700°C versus 1400-1600° for most glasses) and is harder than most glasses.

For liquid scintillators arrays, we recommend attempting to develop a fast liquid scintillator with a high enough index of refraction to allow guiding in glass-capillary arrays. While many high index materials do scintillate and have slow components, the effort and expense of developing and testing liquid scintillator samples appears to be significantly lower and to have a greater chance of success than attempting to create a lower index capillary array.

Fast Segmented Scintillators Using Solid Scintillators

The other option is to develop a fast solid scintillator that can be segmented. While Bi-benzyl has a fast long-term decay, its crystalline nature makes it an unlikely candidate for direct manual segmentation for the small segment sizes required for the NIS. Developing

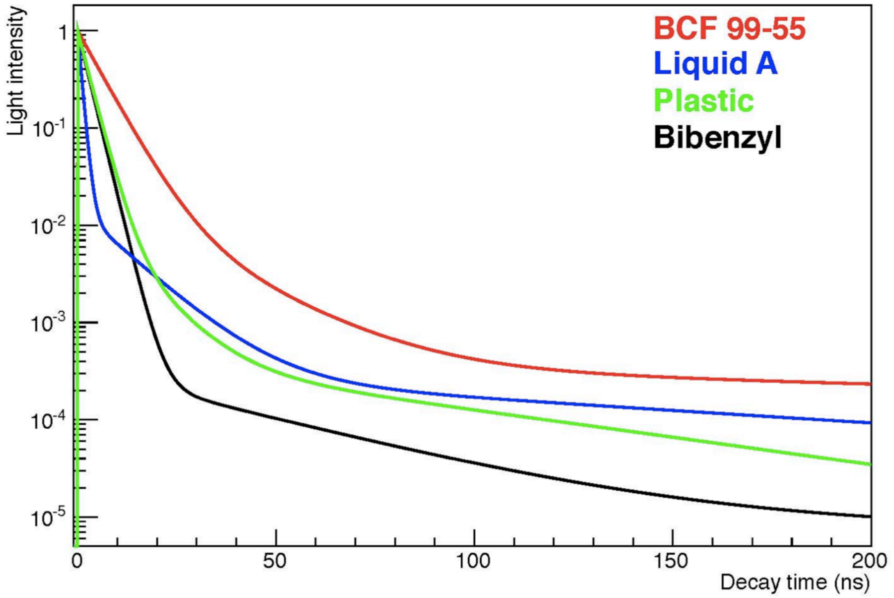

Figure 1 Light decay curves for BCF-99-55, Liquid A, Bi-benzyl and new LLNL plastic scintillator based on PVT.

a fast plastic scintillator that can be drawn into an optical fiber a more likely method.

Efforts to apply the lessons learned in creating Bi-benzyl to a plastic scintillator are under way at LLNL and should be encouraged. It is also possible to crush Bi-benzyl and attempt to incorporate it into a plastic directly; although, scattering effects may limit the performance of such a material as a fiber. Any material produced should not be tested not only for its residual light decay but also for the optical properties such as index of refraction and absorption that could affect its performance when turned into an optical fiber. Any likely candidate material would then need to be transformed into an optical fiber and tested in that form as well.

Since, as mentioned above, better methods of creating fiber arrays will be required to achieve sufficient spatial resolution in the scintillator, we recommend pursuing the improved fiber array manufacturing methods and applying them to the best fast plastic fiber scintillator once it is identified and developed.

c. Impedance-matched high-voltage MCPI drivers

MCPIs using mesh-grid technology are capable of MCPI rise times less than 1 ns, but requires custom engineered, impedance matched high-voltage drivers. We recommend developing such high-voltage drivers to improve the energy resolution of the NIS system, which would improve the accuracy of the scattered neutron measurements, as well as open up the possibility of making spatially resolved ion temperature measurements of ignition implosions.

d. Aperture designs to improve signal-to-noise ratio

The NIS requirements include measuring the imploded shape using Legendre Polynomial fits to obtain P0, P2 and P4. The relevant minimum signal-to-noise level of 10 is defined not at peak but at the 20±5% contour for the primary neutron image. The system is also required to have a signal-to-noise level of 22 at the peak intensity of the downscattered image. Considering the low yields for which the NIS had been used so far, we recommend investigating new aperture designs to improve the S/N performance at low yield. Imaging of weak signals, such as tertiary neutrons could also benefit considerably from improved S/N.

Since the use of penumbral and, in particular, ring-apertures to image neutrons have been shown to produce significant improvements in signal to noise for low-brightness neutron sources[4] and since the CEA has considerable experience with such apertures, a collaboration to field a CEA-produced ring aperture might prove useful. Due to the long length of the current NIS LOS, however, there would need to be additional research on manufacturing technologies for a ring aperture. A magnification of 95, for instance, would require a central plug only 1.2 mm in diameter at the end of a 20-cm penumbra, which is not within the ability of current construction methods. We recommend additional calculation to determine the exact benefits of new aperture designs, which would depend on the yields, the required field of view and the source sizes expected for the experiments. If the calculations show a significant benefit, we would then recommend development of the required aperture technology.

IV. Evolution of the NIS

Here we look at the general approach for upgrading the NIS to improve its performance. The current NIF NIS is optimized for low yields (~10^{15} primary neutrons) with a fiber-coupled imager being used to measure the down-scattered image. Due to the direct coupling of the fiber arm to the scintillator, the current system cannot be easily to test other scintillators or detectors. Moreover, we foresee the need to be continuously acquiring data, so any testing of modifications would best be done on a system that does not perturb the measurements at NIF. Thus we believe that there are two main approaches that will be required.

a. Offline testing

Until the yield increases, we expect to rely on the same methods used for development prior to fielding at NIF, which included tests at calibration facilities and at OMEGA. Both LANL and CEA have imaging systems that can be fielded at OMEGA, and with modifications such as lens coupling they could be used to develop and test high-speed scintillator arrays. Similarly, both LANL and CEA have the ability to field aperture arrays at OMEGA, which would allow tests of new aperture designs.

b. Imaging system modularity to allow comparison testing at NIF

When the yield increases to ~10^{16}, it should be possible to forego the added efficiency of fiber coupling and make the entire system more modular by replacing the fiber-coupled arm with a lens-coupled system for the down-scattered neutron measurement. At that point, the scintillator becomes free standing, which would allow for simple replacement of the current scintillator with any new scintillator. Additionally, since the neutrons passing through the scintillator would no longer be scattered immediately by the fiber taper and fiber rope, it would also be possible to place another scintillator and imager behind the first scintillator. This added imager would allow direct one-to-one comparison testing of scintillators prior to replacement and might also be used for measuring tertiary neutrons at high yields.

We note that this level of modularity would also allow most additional development that might be required to meet future needs for neutron imaging without crippling the existing system for measuring the primary and down-scattered neutrons.

V. Time scales, scopes and abilities of partners

The teams involved in this collaboration have a broad mix of skills and abilities that should be able to develop all the technologies mentioned above. These teams do, however, have different defined scopes and time scales, so understanding the scopes, abilities and timescales

a. Los Alamos National Laboratory

LANL has been the primary designer for the NIF NIS with primary responsibility for the design and manufacture of the neutron pinhole arrays, the DIM cart and the imagers, including the fiber-coupled imager and the lens coupled imager. LANL provides considerable physics expertise and experience in neutron imaging, including data analysis and the manufacture of complex pinhole arrays. LANL also developed and characterized Liquid A with EG&G, Santa Barbara.

LANL has the primary and urgent scope to meet the design requirements, performance qualify the system and provide useful neutron imaging data for the NIC and other High Energy Density Physics (HEDP) experiments.

b. Lawrence Livermore National Laboratory

As the home of the NIF, LLNL has largely been responsible for developing the line of sight, the alignment systems and for integrating the system into the standard operations of the NIF facility. The LLNL physics and engineering team provides physics expertise and experience in neutron imaging. Additionally, LLNL has the ability to draw on the considerable physics and engineering expertise at LLNL, including expertise in the development and characterization of fast scintillators such Bi-benzyl and fast plastic scintillators.

The LLNL team scope and timescale are similar to LANL with more emphasis on integration of the system into standard NIF operations.

c. Commissariat à l'énergie atomique, DAM

The CEA is an organization with extensive experience in neutron imaging. In this collaboration, the CEA provides a strong understanding of penumbral and ring-aperture imaging and unique expertise in the manufacture, cleaning and filling of high-quality liquid-scintillator-filled glass-capillary arrays.

The scope of the CEA neutron imaging team is aimed at the long-term development of imaging systems for Laser Mégajoule (LMJ). Thus their focus needs to include development of systems that are useful at LMJ, and their effort level could only be modest but could be expected to extend over several years. While the best means of approaching that scope would be the development of an additional line-of-sight at NIF, development of high-quality fast scintillator arrays, novel aperture arrays and data analysis methods would also be useful.

d. National Security Technologies

National Security Technologies (NSTec), formerly known as EG&G and Bechtel Nevada, has long experience in the engineering of imagers for neutron imaging both at Livermore Operations (LO) and Los Alamos Operations (LAO). LAO’s relevant expertise includes design of the coupling lens for the NIF NIS. LO has extensive knowledge of CCD-camera and gated-MCPI development, coupling and characterization as well as facilities and expertise for spatial characterization of segmented scintillators.

NSTec LO has the scope for calibration of diagnostics at NIF and is also capable of working via contract on design, engineering and manufacture of diagnostic components and systems.

VI. Summary and Recommendations

In this whitepaper, we have identified three main drivers for design improvements to the NIS: the need to meet the 10-µm spatial resolution requirement, the reduction of the residual scintillator light to improve imaging of down-scattered neutrons and the improvement of the image S/N ratio to improve the reconstructed data quality.

To meet the 10-μm spatial-resolution requirement, we recommend improving the spatial coherence of the NIS scintillator by:

1) Developing a liquid capillary array for use with liquid scintillators at NIS
2) Developing improved manufacturing methods for optical fiber arrays

To reduce the residual scintillator light and improve imaging of the down-scattered neutrons, we recommend:

3) Developing a high-index fast liquid scintillator that could be incorporated into the liquid capillary array.
4) Developing a fast plastic scintillator to be incorporated into the improved optical fiber arrays. This will require optical testing of the bulk material and the material in optical fiber form.
5) Final selection of the either the fast liquid scintillator array or the fast plastic scintillator array based on the performance of the arrays both in terms of spatial resolution and residual light.
6) Developing impedance-matched high-voltage MCPI drivers.

To improve the S/N, we recommend:

7) Additional calculation to determine the exact benefits of new aperture designs, which would depend on the yields, the required field of view and source sizes expected for the experiments.
8) Development and manufacture of the aperture technology selected through the calculations.

To allow testing of the recommended new hardware, we recommend:

9) Offline development and testing of most hardware.
10) Initial neutron testing at OMEGA, if necessary.
11) Replacement of the fiber-coupled imager with a lens coupled imager, once higher yields are achieved, to allow more modular replacement of scintillators.
12) Addition of an additional scintillator and imager station on NIS, to allow direct tests of current and new technology, which would also create the potential for imaging tertiary neutrons without affecting the primary and down-scattered imaging.

Considering the scope, timescales and expertise of the various teams, we believe that the fast liquid scintillator array development and improved aperture design should largely be performed as collaborations between CEA and LANL. Fielding of the improved aperture at NIS would also involve LLNL for development of the alignment. The development of a fast plastic scintillator array with improved spatial coherence should largely be performed as a collaboration between LLNL and NSTec LO. We expect that final testing and selection of the scintillator arrays would involve all the teams. The replacement of the fiber-coupled imager with a lens coupled imager and the addition of the new scintillator and imager station on NIS would be LANL with LLNL performing its normal NIF integration functions.

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