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Neutron radiation shielding for the NIF streaked x-ray detector (SXD) diagnostic

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The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) is preparing for the National Ignition Campaign (NIC) scheduled in 2010. The NIC is comprised of several "tuning" physics sub-campaigns leading up to a demonstration of Inertial Confinement Fusion (ICF) ignition. In some of these experiments, time-resolved x-ray imaging of the imploding capsule may be required to measure capsule trajectory (shock timing) or x-ray "bang-time". A capsule fuelled with pure tritium (T) instead of a deutriun-tritium (DT) mixture is thought to offer useful physics surrogacy, with reduced yields of up to 5e14 neutrons. These measurements will require the use of the NIF streak x-ray detector (SXD). The resulting prompt neutron fluence at the planned SXD location (~1.7 m from the target) would be ~ 1.4e9 /cm^2. Previous measurements suggest the onset of significant background at a neutron fluence of ~ 1e8 /cm^2. The radiation damage and operational upsets which starts at ~ 1e8 rad-Si/sec must be factored into an integrated experimental campaign plan. Monte Carlo analyses were performed to predict the neutron and gamma/x-ray fluences and radiation doses for the proposed diagnostic configuration. A possible shielding configuration is proposed to mitigate radiation effects. The primary component of this shielding is an 80 cm thickness of Polyethylene (PE) between target chamber center (TCC) and the SXD diagnostic. Additionally, 6-8 cm of PE around the detector provide from the large number of neutrons that scatter off the inside of the target chamber. This proposed shielding configuration reduces the high-energy neutron fluence at the SXD by approximately a factor ~50.

I. INTRODUCTION

The ignition campaign at the NIF is comprised of several "tuning" physics sub-campaigns leading up to a demonstration of ICF ignition. In some of these "tuning" experiments, time-resolved x-ray imaging of the imploding capsule may be required to measure capsule trajectory by radiography or x-ray "bang-time" from emission. These measurements will require the use of the NIF SXD, which uses a charged-coupled device CCD to record data. A capsule fuelled with tritium (T) only instead of a DT mixture is thought to offer useful physics surrogacy, with a reduced yield of 5e14 neutrons (note: 1e19 neutrons are expected for the capsule fuelled with DT). A fuel of deuterium-deuterium (DD) would not provide the required beta decay needed to create a smooth layer of frozen hydrogen. However, tritium-tritium (TT) fuel has some deuterium impurities and the resulting neutrons from the DT reaction are comparable in number to the neutrons produced by the TT reaction. The resulting neutron fluence at a planned SXD location (1.7 m from TCC) inside the NIF target chamber would be ~ 1.4e9 /cm^2 direct from TCC. Past measurements[1] suggest that neutron fluence ~1e8 /cm^2 marks the onset of significant background issues. The radiation damage and operational upsets which starts at ~1e8 rad-Si/sec must be taken into account in the design and operation of all the diagnostics. The accumulated radiation damage to the detector is also a factor to be considered in its operational lifetime. The main purpose of the current Monte Carlo neutronics analysis is to predict the neutron and gamma/x-ray radiation dose for the SXD diagnostic in the proposed configuration and to identify possible shielding configuration to mitigate radiation effects.

II. METHOD OF ANALYSES

II.A. Computer Code and Calculation

TART2002[2] is a three dimensional multi-group neutron and photon Monte Carlo transport code, which features a 616-group neutron and 701-point gamma cross-section structures. TART2002 was used to model the NIF chamber and SXD diagnostic. Neutrons and neutron-induced gamma rays were tracked with time dependence through the geometry. The most significant piece of information being the amount of energy deposited from neutrons and gamma/x-ray into the detector.

II.B. Computational Model and Neutron Sources

To analyze the level of neutron and gamma/x-ray radiation dose on the SXD diagnostic, a simple three-dimensional TART2002 model was developed. This model include a 550 cm radius spherical simplified target chamber, 40 cm of 'shotcrete' (concrete) surrounding 10 cm of aluminum (Al-5083) chamber wall and 1.2 m long of the SXD diagnostic as shown in Fig. 1. Inside the chamber, 1.4 cm thick outer aluminum airbox and 0.1 and 0.636 cm thick inner steel cases for the SXD/CCD diagnostic were modeled as a cylindrical shape placed from 103.3 cm to 244 cm from TCC.

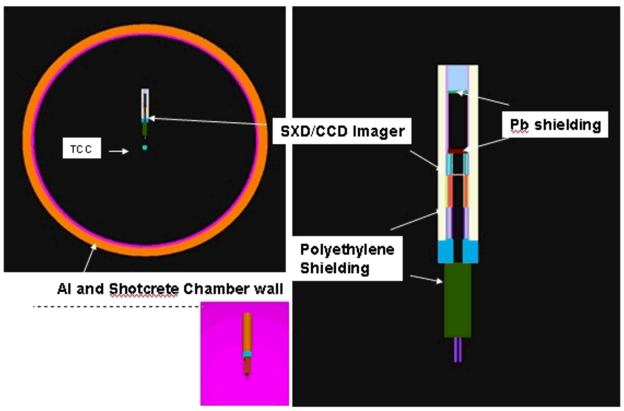

Fig.1 TART model for SXD located inside NIF chamber with PE and Pb shielding around the diagnostic

Fig. 2 illustrates the SXD diagnostic modeled, the first ~70 cm of SXD and CCD camera zones followed by ~50 cm of the airbox electronics zone. For shielding configuration, the PE and Pb shielding were applied at the front, back and around of Al airbox. The thicknesses of the PE shielding are 80 cm in front, 20 cm in back and 6-8 cm around the diagnostic. The Pb shielding thickness is 2.5 cm in the back of both CCD camera and airbox electronics zones.

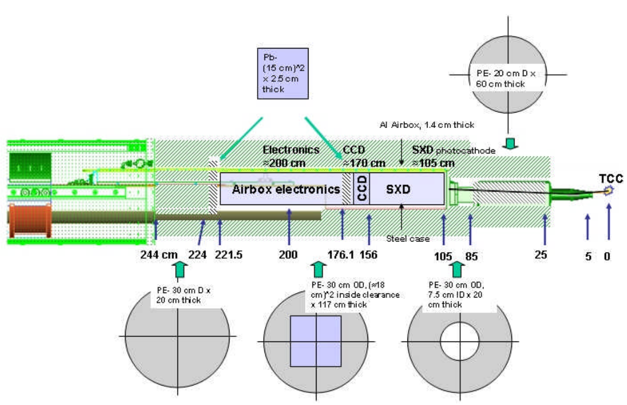

Fig. 2 Details of PE and Pb shielding around SXD diagnostic

The calculations were performed with both a mono-energetic DT neutron source (14.1 MeV) and a continuous TT neutron spectrum source[3] (see Fig. 3) located at the ICF target location, center of NIF chamber as shown in Fig. 1.

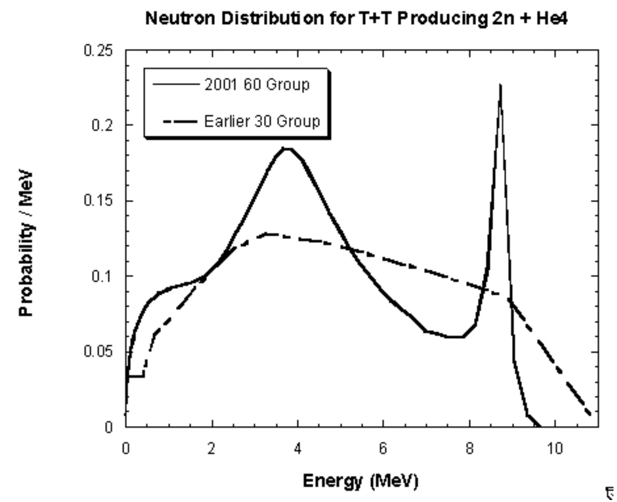

Fig.3 TT neutron spectrum used in the analysis

II. SHIELDING REQUIREMENTS

Previous measurements[1] suggest the onset of significant background at a neutron fluence of ~ 1e8 /cm^2. This background along with the radiation damage and operational upsets which start at ~ 1e8 rad-Si/sec must be factored into an integrated experimental campaign plan. The details of detected background and upsets are device specific and require further study. Additionally, the total weight of diagnostic including all shielding can not exceed the 125 kg due to pointing and operational requirement. Note that use of a high-energy x-ray mirror allows shielding between TCC and the SXD diagnostic.

III. ANALYSIS AND RESULT

Monte Carlo analyses were performed for the configurations with and without shielding, for both 14.1 MeV DT and a continuous TT fusion neutron sources. The prompt neutron and neutron induced gamma doses (rad-Si) and dose rates (rad-Si/sec) for shielding analysis were calculated at various locations, but we give results only for inside the SXD at the location of the CCD.

III.A. SXD without shielding

We considered a configuration without shielding to show the effect of neutron scattering off chamber components and the need for side shielding. For the DT source neutron case, scattering of primary 14.1 MeV neutrons with the aluminum chamber and other structures inside chamber contributes ~40 % of the neutron fluence below 14.1 MeV at the SXD location. The continuous TT neutron spectrum source has two peak energies, 8.8 and 3.7 MeV. The peak neutron spectrum around 8.8 MeV is slightly reduced by scattering along the line of sight to this location by existing SXD hardware. The neutron spectrum for both DT and TT source neutron cases is shown in Fig. 4.

Including the effect of scattering, the prompt neutron and gamma dose is calculated for both DT and TT source neutron cases. For sources of 5e14 neutrons, the prompt neutron and gamma doses are ~ 1.89 and ~0.4 rad-Si for the DT neutron source case and ~0.26 and ~0.13 rad-Si for the TT neutron source case at the CCD camera location (1.7 m cm from TCC), as shown in Table 1.

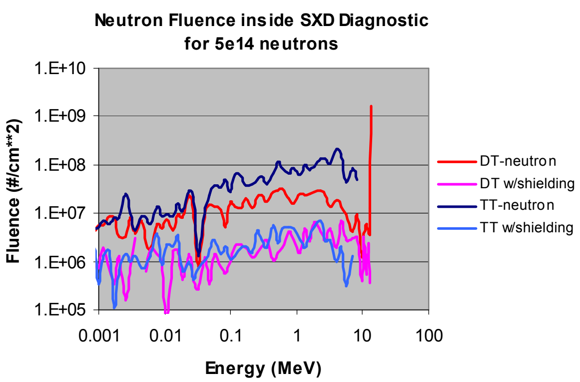

Fig. 4 Neutron Fluence for 5e14 source neutrons inside SXD with and without shielding for DT and TT neutron case.

	DT neutron (rad-Si)		
	Gamma	Neutron	Total
W/O Shielding	3.97E-01	1.89E+00	2.29E+00
W/PE Shielding	3.14E-01	6.71E-03	3.21E-01
W/PE+Pb Shielding	2.78E-01	6.45E-03	2.85E-01
	TT neutron (rad-Si)		
W/O Shielding	1.34E-01	2.56E-01	3.90E-01
W/PE Shielding	2.50E-01	4.74E-03	2.55E-01
W/PE+Pb Shielding	2.27E-01	3.90E-03	2.31E-01

Table 1. Total prompt neutron and gamma doses with 5e14 source neutrons for cases considered

For both the DT and TT neutron source cases without shielding, the neutron dose is dominant. The higher neutron dose for the DT neutron case is attributed to the larger high-energy (14.1 MeV) neutron fluence than the TT neutron case. The main source of the gamma dose is the neutron-induced gamma from the 10 cm thick of aluminum chamber.

The neutron and gamma dose rates as a function of time for 5e14 source neutrons are shown in Fig. 5. It may be noticed that the gamma dose starts earlier than the neutron dose at the SXD camera zone. This is due to the neutron-induced gammas produced in the portions of the SXD structure closed to TCC. The maximum total (neutron + gamma) dose rates for 5e14 source neutrons are ~1e9 and 3e7 rad-Si/sec for DT and TT source neutron cases. The larger maximum dose rate for DT associated with deuterium impurities in the TT fuel is the major concern. Without shielding around the diagnostic, the neutron fluence (~3e8 neutrons/cm^2 for 5e14 TT source neutrons) is too large and the actual maximum total dose rates with deuterium impurities could be larger than the proposed requirement.

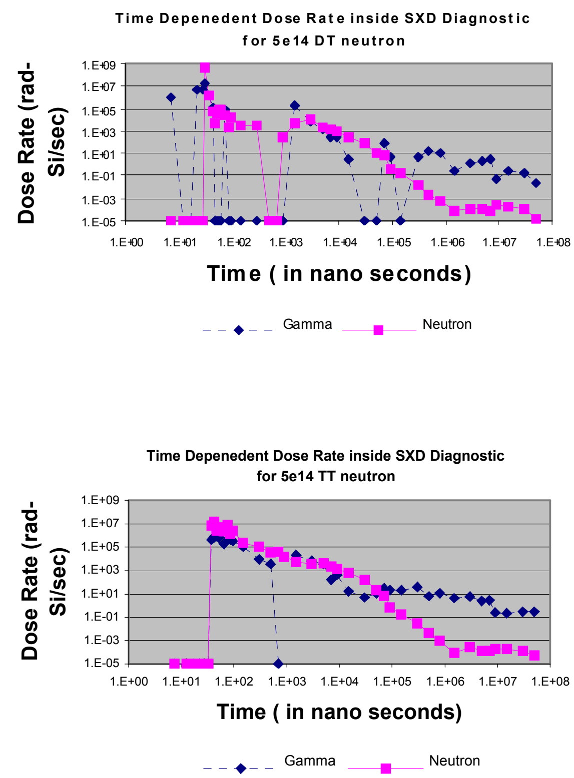

Fig. 6 Time dependent Dose rates inside SXD for both 5e14 DT and TT neutrons source cases without shielding

III.B. SXD with PE shielding

To reduce high-energy neutron fluence and radiation dose/dose rate at the SXD diagnostic, PE was considered as a shielding material. PE is light and a very good neutron moderator. It has ~20 cm of mean free path for high (~ 6-8 MeV) energy neutrons, therefore, applying ~50 cm PE around the diagnostic can reduce the neutron fluence by a factor of 10. For this reason, an 80 cm of the PE shielding between TCC and the SXD diagnostic, an additional 6-8 cm around the detector and a 20 cm shielding in the back of the camera were applied to mitigate high energy neutron contribution to the diagnostic as shown in Fig. 2. The total resulting PE shielding weight is ~140 kg in this case.

The overall high neutron flux at the SXD diagnostic for both DT and TT neutron cases was reduced by 50 times as seen in Fig. 4. Due to the high energy neutron moderation inside the PE shielding material around the diagnostic, the 14.1 and 8.8 MeV peaks present in the previous DT and TT neutron spectrum without any shielding are removed and the larger resulting lower energy neutron fluence is seen in Fig. 4. The fraction of the neutron fluence around those peak energies to the total energy integrated fluence is reduced to less than 1-5 %.

Although substantial amount of neutron fluence reduction was obtained by applying the PE shielding around the diagnostic, the gamma fluence reduction is not as large as the neutron fluence reduction as shown in Fig. 6. PE is not an effective attenuator of gamma rays and some additional production of gamma radiation is expected from the down scattered low energy neutron reactions inside the PE shielding material.

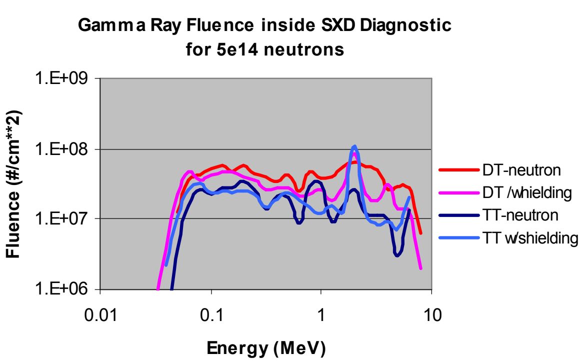

Fig. 6 Gamma ray Fluence for 5e14 source neutrons inside SXD with and without shielding for DT and TT neutron case

The total gamma fluence for the DT neutron case was reduced by 20-30% over the whole energy range. However, for TT neutron case, the gamma fluence shows a larger peak around 2-3 MeV as seen in Fig. 6. This is due to the additional gamma ray production inside the PE by the down-scattered neutrons.

For sources of 5e14 neutrons, both the prompt neutron and gamma doses were reduced with PE shielding. As shown in Table 1, the prompt neutron doses were reduced to ~0.007 and ~0.005 rad-Si and the gamma doses were reduced to ~ 0.31 and 0.25 for DT and TT neutron source cases, respectively. For both the DT and TT neutron source cases, the gamma dose is dominant with PE shielding but the total neutron and gamma doses are reduced to ~0.32 and 0.26 rad-Si compared to the cases without PE shielding. The maximum total (neutron + gamma) dose rates, as shown in Fig. 7, are also reduced to ~2e7 and 5e5 rad-Si/sec for the DT and TT neutron source cases. Both the neutron fluence and the maximum total dose rate with shielding around the SXD diagnostic were reduced by approximately a factor of ~50 and meet the proposed requirement.

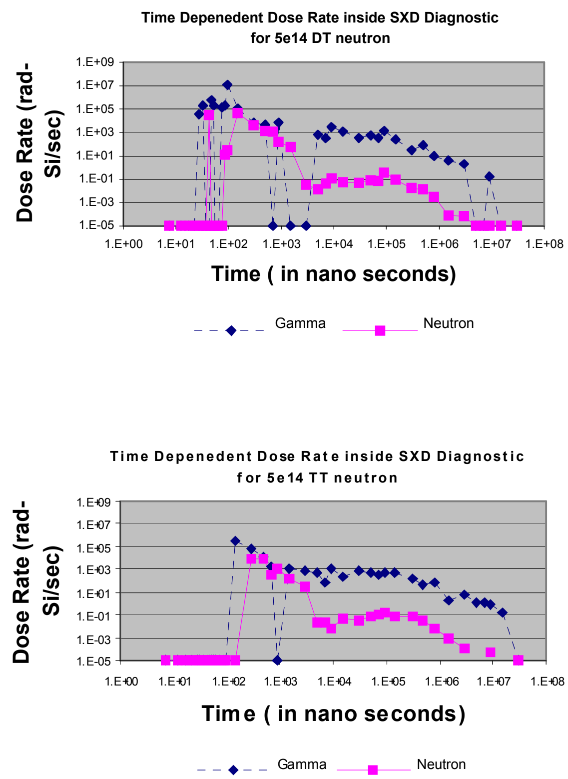

Fig. 7 Time Dependent Dose rates inside SXD for both 5e14 DT and TT neutron source cases with PE shielding around the diagnostic

III.C. SXD with PE and Pb shielding

In addition to the PE shielding around the diagnostics, 2.5 cm thick Pb shielding was applied in the back of the CCD camera and airbox electronics zones to obtain additional shielding from scattered neutron and neutron induced gamma from the aluminum chamber. Compared to the previous case having PE shielding only, total dose is decreased by ~10 to 15% for both DT and TT neutron cases as shown in Table 1.

IV. CONCLUSION

To prevent the radiation damage on the SXD diagnostic through the detected neutron background or electronic upset by high energy neutron fluence during the several "tuning" physics sub-campaigns at NIF, PE and Pb shielding were considered to reduce the high energy neutron fluence and dose/dose rates. With placement of an 80 cm of PE shielding between TCC and the SXD diagnostic and an additional 6-8 cm of PE and 2.5 cm of Pb around the detector allowing for the large number of neutrons that scatter off the inside of the target chamber reduces both the neutron fluences and the maximum total dose rates at the SXD diagnostic by approximately a factor of ~50 and meet the proposed requirement. SXD weight with current shielding design is ~10% over requirement. Optimization of shielding design should meet weight requirement.

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