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Z. M. Liao, M. Nostrand, W. Carr, J. Bude, T. I. Suratwala

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Modeling of laser-induced damage and optic usage at the National Ignition Facility

Zhi M. Liao*, Mike Nostrand, Wren Carr, Jeff Bude, and Tayyab I. Suratwala
Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA, USA 94550

ABSTRACT

Modeling of laser-induced optics damage has been introduced to benchmark existing optic usage at the National Ignition Facility (NIF) which includes the number of optics exchanged for damage repair. NIF has pioneered an optics recycle strategy to allow it to run the laser at capacity since fully commissioned in 2009 while keeping the cost of optics usage manageable. We will show how the damage model is being used to evaluate strategies to streamline our optics loop efficiency, as we strive to increase the laser shot rate without increasing operating costs.

Keywords: laser induced damage, optics lifetime

1. INTRODUCTION

Laser-induced damage in optics is a critical element in managing the operation of megajoule (MJ)-class lasers such as National Ignition Facility (NIF)[1,2] for inertial confinement fusion (ICF) and high energy density science experiments. Decades of studies on this topic have yielded a much better understanding of the initiation and growth[3-16] of laser-induced damage in optics, although most of the research was done in offline facilities with limited area sampling. Recent damage initiation modeling results of NIF operation[17] have shown that offline damage testing results are consistent with online operation data. However, the previous online studies[17] have been heavily focused on the initiation of damage sites on fused silica optics under UV illumination while damage growth usually limits the operation of NIF[18]. The early recognition of the potential consequences of laser-induced damage on NIF high-fluence operation have helped shepherd the development of the NIF loop processes to mitigate the effect of laser-induced damage on the operation of the laser facility.

The NIF loop strategy[19] consists of recycling optics by repairing individual damage sites, thus allowing a single optic to be used multiple times before it needs to be refinished or replaced (Figure 1). This assures that NIF can operate at the maximum energy while minimizing the cost of replacing optics. Currently, NIF uses localized intra-beam light blockers to temporary impede the growth of the laser-induced damage sites that are on the verge of growing too big to be repaired[19]; however there is a limit on how many of these blockers can be deployed for each laser beam. As a result, the length of time an optic may remain installed is determined by the growth rate of these damage sites. In this work, we will present simulation results using our damage model (OpticsX) which show the ability to predict the loop operation of NIF fused silica final optics – the wedged focus lens (WFL) and the grating debris shield (GDS) – which function as the focusing element and the diagnostic element (for laser energy sampling) for NIF (see Figure 1), respectively. These results can help support our supply planning as they provide verification that our model is able to properly predict the usage of optics in support of laser operation. Furthermore, this would be an invaluable tool as we strive to improve the efficiency of the NIF Loop.

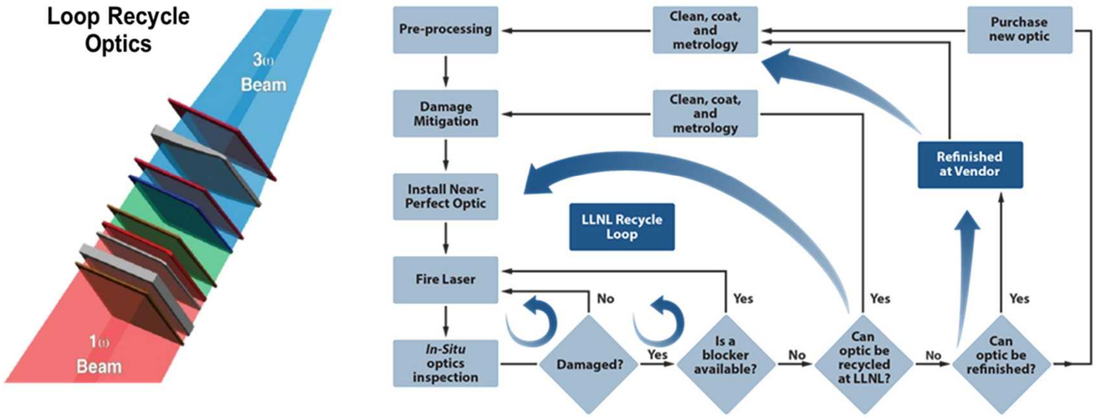

Figure 1: NIF loop recycle schematic which including the final 3ω optics: wedged focusing lens (WFL) and the grating debris shield (GDS)

2. METHODOLOGY

The optics recycle loop allows laser-induced damage to initiate and grow online with the damage status being frequently updated using the NIF in-situ optics inspection system (FODI[20,21]) to ensure damage sites do not grow to a size beyond which they can be repaired. [22] Sites close to this size limit can be blocked, which consists of placing an opaque mask on the laser beam spatially in line with where the damage site is located, preventing further laser exposure of the damage site and thus arresting its growth. However, too many blockers will directly reduce the energy output of the beams, as a result, there is a limit on number of blockers allow on a quad (i.e. 4 adjacent beams of NIF). Once the maximum blockers on a quad are reached, then one of the optics is removed to be repaired – usually the optic with the most blockers. The optic is then sent to the mitigation facility where all the FODI-identified damage sites are laser repaired and the optic can be put back online. Although optic usage is due directly to laser-induced damage initiation and growth, currently optic usage is driven by damage growth. This is because we are running the laser in a regime where we have more damage sites per optic than available blockers. In this regime, the number of damage sites does not scale linearly with how long an optic can last before it needs to be exchanged. Table 2 shows simulation results on changes on exchange rates (i.e. how many shots an optic can last) vs. the number of damage sites for various initial damage site sizes (D_o). It shows that a 10x increase in damage sites does not yield a 10x increase in exchange rate but a fraction of it; this is because it only takes the fastest growing sites to determine the exchange rate, and these competitions to become the fastest growing sites scale sub-linearly. Consequently, having a larger initial damage size reduces the sensitivity of number of damage sites on exchange rate. The relative insensitivity of the number of damage sites allow us to seed each optic with estimate number of damage sizes that our online inspection system (FODI) provides. Due to the resolution of the FODI, the initial size we use is 35 μm. This does not necessarily mean that there aren't damage sites under 35 μm, just that these smaller sites do not impact the exchange rates.

Table 1: Simulation covers a large number of shots and the resultant exchanges for both WFL and GDS.

Initial Size D_0 (μm)	**N=10 Sites (shots till exchange)**	**N=100 Sites (shots till exchange)**	**Increases in exchange rate**
15	1250	375	3.3x
25	500	130	3.8x
35	110	80	1.4x

For this study, we will focus on the growth component of the model to attempt to predict the number of the exchanges for both WFL and GDS on each of the 192 beamlines of NIF from 2013 to spring of 2015. Although NIF has been operational since 2009, we choose 2012 as the start date because of the evolution of the optics processing and our exchange strategy began to mature. This is an extensive effort as 2+ years of operation consists of tens of thousands of beamline-shots (i.e. shots participated by each beamline) (see Table 1). We choose beam-shots because although NIF consists of 192 beamlines, not all beamlines participate in every shot. For example, some shots will have 192 beamlines participate (192 beamline-shots) and some will have only 4 beamlines participate (4 beamline-shots). The shot history of each beamline is first gathered along with its laser shot parameters (i.e. shot energy, pulse shape, etc.). Furthermore, because each beamline has its own unique shot history, it also has its own unique optic exchange history. In order to accurately present the initial and final condition of the shot history, the starting point of each simulation begins when an optic is exchanged online and ends at when the optic is last exchanged. This means that each beamline will have a slightly different start and end date as well as the number of shots simulated. Furthermore, there is a separate, distinct shot plan for WFL and GDS (because WFL and GDS are exchanged independently of one another). As a result, the total shots for WFL and GDS simulated are slightly different because of when an optic is first installed in 2013 and last removed in spring of 2015 for each beamline.

Table 2: Simulation covers a large number of shots and the resultant exchanges for both WFL and GDS.

	Beamline Shots	Exchanges
WFL	~42,000	~600
GDS	~59,000	~1,600

The same simulation parameters used for the WFL were applied to simulate GDS exchange with only a few adjustments. One adjustment is that the GDS has a smaller beam area and hence 3.5% higher fluence due to focusing of the WFL (see Figure 1). Furthermore, more damage is observed on the GDS above and beyond what can be accounted for by the higher fluence. We adjust the difference in the number of damages sites accordingly to reflect the observed data (GDS ~ 75 sites/optic, WFL ~20 sites/optic). A potentially important difference between how the system is actually operated and how we ran our simulation, is that in our simulation each beam for each optic type is being simulated independently. In operation, every four neighboring beams (i.e. a quad) share the same input from master oscillator and share the same blocker allocation (20/quad). In our simulation, we assume that each beam has the same proportional blocker allocation. At first glance, it would seem that 20 blockers allocated to 4 identical beams (with 2 optics (WFL + GDS) per beam) would yield only 2.5 blockers per beam per optic. However, because of the nature of the exchange strategy, the optics installation dates across a quad becomes staggered. As a result, the recently installed optics need few or no blockers making an average of 5 available for the optics near the end of their installation. Hence we used an average blocker availability of 5 for each simulation.

3. RESULTS

The WFL data set consists of over 42,000 beam-shots or an average of around 220 shots per beam. If we plot the total accumulated exchanges across the 192 beams, it will be ~600 exchanges (see Figure 2). If we integrate all of the exchanges across NIF and plot vs. time, we can see that our projections are within ~16%. The GDS analysis data set consist of over 59,000 beam-shots which results to around 300 shots per beam. If we plot the total accumulated exchanges across the 192 beams, it comes to ~1600 exchanges (see Figure 2). The results indicate that our prediction generally lags over time, under-predicting by ~17% after 24 months.

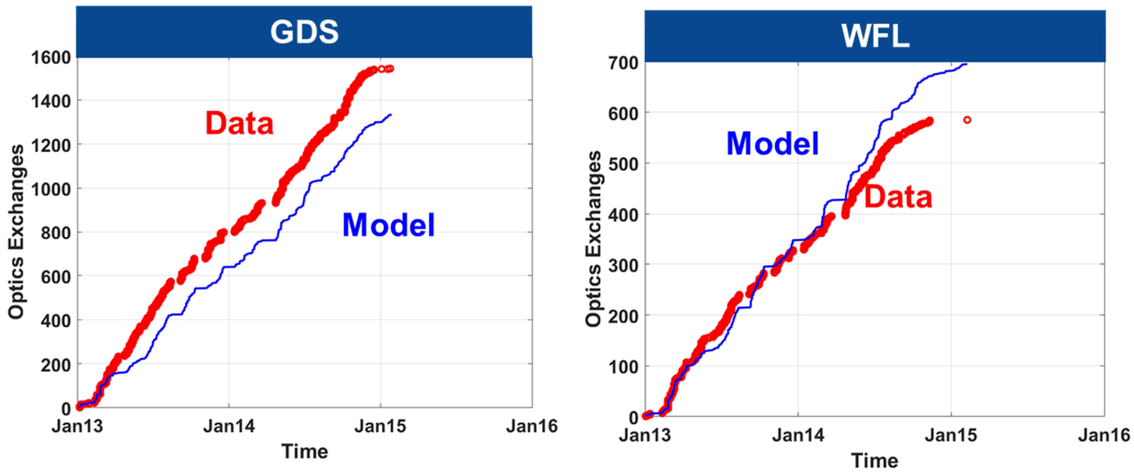

Figure 2: Plot of number of optics exchange vs. time comparing the data vs. model for GDS (left) and WFL (right).

However, as we have discussed, the WFL and GDS optic exchanges are governed by shared blocker availability so if the operator at any given moment in time decides to preferentially exchange WFL instead of GDS, it would change the trajectory of each optics exchange. In this regard, we should combine the results of both WFL and GDS with respect to our model results. Note the loop costs are virtually the same for both optic types. Figure 3 plots the accumulated damage initiation and exchanges combining both WFL and GDS optics. The model was remarkable in that it was able to correctly predict to within 5% of the total number of optics exchanged.

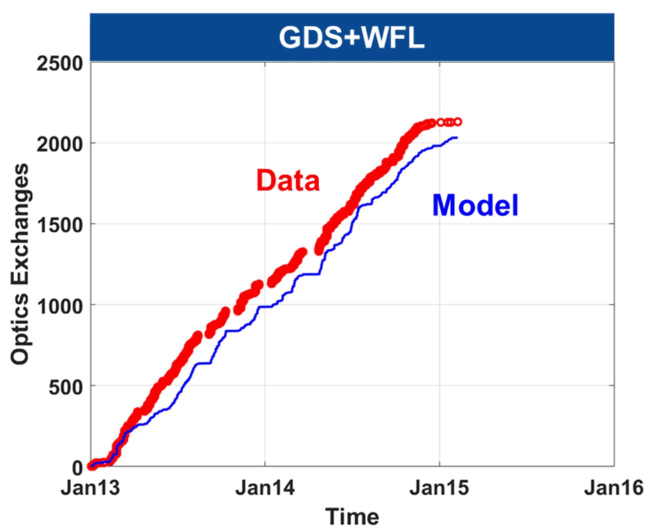

Figure 3: Plot of number of optics exchanges vs. time with both GDS and WFL added together shows the excellent agreement between data and model.

4. CONCLUSIONS

Damage modeling for NIF allows calculation of optics usage in support of the NIF optics loop strategy. We have demonstrated our ability to simulate the recycle loop process which is based on accurate modeling of the damage process as well as the operator's rules of engagement. We are able to predict the exchange rates for NIF (2012-2015, ~60,000 shots) within 95% accuracy using our model. This validates our improved understanding of the relevant parameters and behaviors that contribute to optics usage and is a potential valuable tool for predicting future operation strategies.

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