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Tools for Predicting Optical Damage on ICF-Class Laser Systems

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Introduction

Operating a fusion-class laser to its full potential requires a balance of operating constraints. On the one hand, the total laser energy delivered must be high enough to give an acceptable probability for ignition success. On the other hand, the laser-induced optical damage levels must be low enough to be acceptably handled with the available infrastructure and budget for optics recycle. Our research goal was to develop the models, database structures, and algorithmic tools (which we collectively refer to as "Loop Tools") needed to successfully maintain this balance.

Predictive models are needed to plan for and manage the impact of shot campaigns from proposal, to shot, and beyond, covering a time span of years. The cost of a proposed shot campaign must be determined from these models, and governance boards must decide, based on predictions, whether to incorporate a given campaign into the facility shot plan based upon available resources.

Predictive models are often built on damage "rules" derived from small beam damage tests on small optics. These off-line studies vary the energy, pulse-shape and wavelength in order to understand how these variables influence the initiation of damage sites and how initiated damage sites can grow upon further exposure to UV light. It is essential to test these damage "rules" on full-scale optics exposed to the complex conditions of an integrated ICF-class laser system. Furthermore, monitoring damage of optics on an ICF-class laser system can help refine damage rules and aid in the development of new rules. Finally, we need to develop the algorithms and data base management tools for implementing these rules in the Loop Tools. The following highlights progress in the development of the loop tools and their implementation.

Background

The optics maintenance and recycling strategy ("Loop Diagram", see Figure 1) enables maximum operational energy and facility utilization at any point in time. The strategy involves inspecting the optics after a laser shot for damage. If damage is present, try to 1) block the site

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in-situ using beam blockers, 2) recycle the optic via onsite mitigation, or 3) refinish the optic at the vendor. Our goal is to enable this strategy through the development of “Loop Tools”.

The Loop Diagram also introduces some key concepts utilized in the development of the Loop Tools. After optics are installed and the laser is fired, the optics are imaged in-situ with a CCD-based automated system called FODI (Final Optics Damage Inspection, see Ref. 1). These images are automatically processed by OI (Optics Inspection), which is an in-house software package that analyzes the images for flaws, and determines the flaw size through radiometry (see Refs. 2, 3).

Since flaws will only grow above a threshold fluence, an efficient strategy to prolong optic lifetime is to locally reduce the fluence at a flaw site below the threshold level. This is accomplished by adding a “blocker” within the laser beam (see Ref. 4). The blocker is an amplitude mask inserted into the laser beam that attenuates a small portion of the full-aperture beam, essentially creating a “hole” in the beam at the location of the damage site. Blockers are an efficient solution since the optic doesn’t need to be exchanged. With this strategy, optics only need to be exchanged after the optic blocker count reaches the maximum allowed based on total beam obscuration.

When an optic needs to be exchanged, it can be recycled through a process referred to as “mitigation”. Mitigation is a process where the local damage site is physically removed or repaired in an off-line facility. Current techniques for fused-slica optics use a focused CO_2 laser beam to excavate the site, leaving behind a small, smooth cone that is resistant to further laser damage (see Ref. 5). After mitigation, the optic can be re-installed on the system. Currently, damage sites eligible for mitigation are restricted by a lateral size known as the maximum allowed size or pull-size. Blockers are applied before the damage site is predicted to exceed the pull-size.

If an optic cannot be mitigated, the next option is to refinish it at the vendor. This involves removing material over the entire surface of the optic to create a new (but slightly thinner) optic. If the optic cannot be refinished (for example if doing so would make the optic too thin), the optic is no longer useful and must be discarded. This is the least efficient strategy for most optics.

Central to the Loop Tools predictive capability is the “Damage Calculator”. Using the rules developed from online data, this model predicts the initiation of new damage sites, and the growth of existing damage sites. In other words, it takes in the current damage state of the system and the proposed laser shot parameters and calculates a new (post-shot) damage state. From these predictions, actionable plans can be generated: optic exchange plans, blocker plans, and inspection plans, for example.

The proposed laser shot parameters, such as pulse shapes and fluence distributions, are computed by LPOM, the Laser Performance and Operations Model, developed at LLNL (see Ref. 6).

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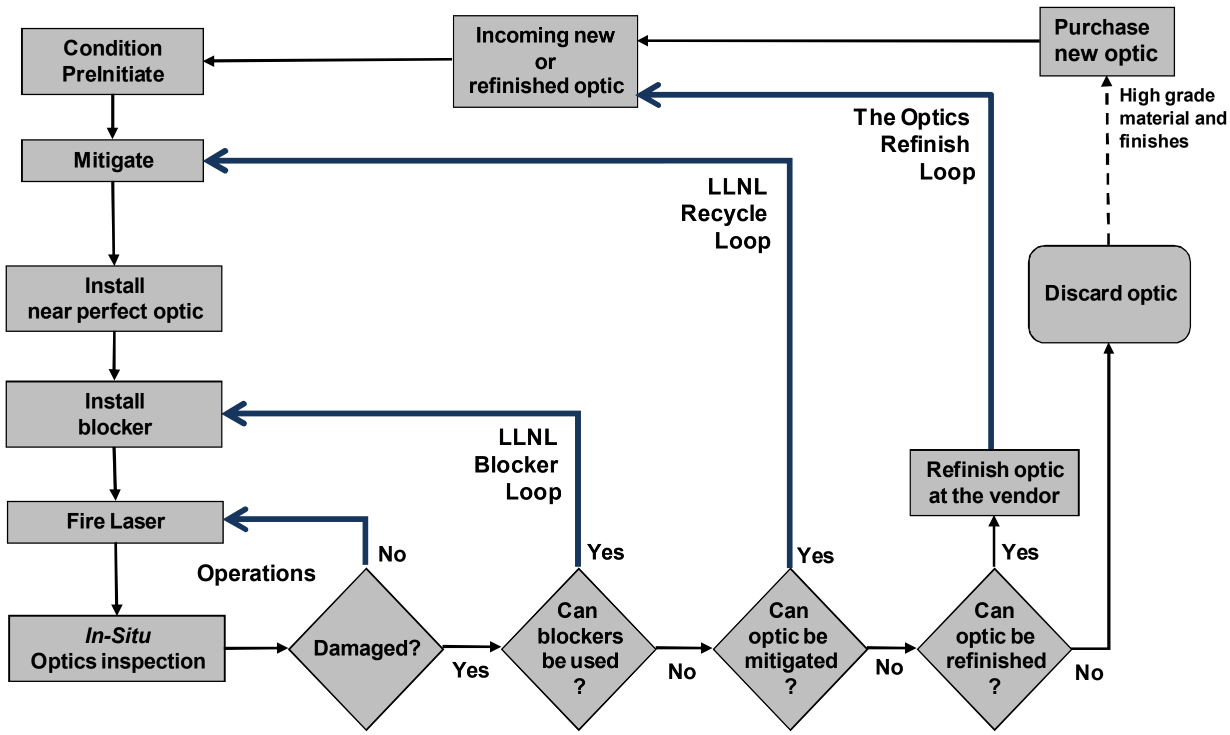

Figure 1) The "Loop Diagram" illustrates the optic recycle strategy

The rules used by the Damage Calculator have been the subject of intense study (see for example, Refs. 7-11). These algebraic rules typically come in the form of damage probability density (ρ) as a function of scaled fluence (Φ). The fluence is scaled to a damage initiation equivalent (DIE). That is, many factors influence how much damage a given laser fluence will inflict, including wavelength, pulse width, and pulse shape. Many small beam offline studies have focused on how to convert a given pulse shape into a DIE fluence for a given optical surface (see Refs. 12,13). These rules are at the core of the predictive capability of the damage state of the laser system.

FODI inspections and the identification of growing sites

Loop strategies for final optics maintenance require detailed tracking of individual defect sites in order to recognize sites that can grow and exceed the pull-size criteria as well as a list of defect sites that should be mitigated. The extreme sensitivity of FODI allows for comprehensive inventory of all possible defect sites, but the large number of candidate sites (including noise, reflections, ghosts, etc) makes it difficult to identify the "most threatening" sites that grow with fluence. In the past, it has been difficult to unambiguously define "growing sites" based on FODI images. To this end, we have developed the following rules based on our understanding of FODI and OI capabilities and accurate characterization of growth from off-line experiments. As the capabilities of FODI and OI changes, these assumptions must be updated in order to maintain consistency.

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1. Persistence. To filter out spurious or “ghost” sites (e.g. hardware reflections, stray external light sources, scattering from debris and contamination) that appear and disappear over time), at least three consecutive observations are required in order to identify the defect as a ”persistent” damage candidate.

2. Measurement Accuracy. In order to develop rules for whether a candidate damage site is actually growing in size, it is necessary to assess the measurement accuracy of FODI acquisition and analysis. FODI has a spatial resolution of about 100 microns per pixel. In addition, and perhaps more importantly, the sum of intensities scattered by a site (radiometrics) can be correlated to defect area. In this way, we can determine the confidence for measurements as follows:

   a. For sub-resolution defects (illuminated with normal edge lighting) radiometrically estimated at 50 um or below, we can size with at best $\pm$ 50% accuracy. Therefore a defect’s size over time should have to increase by >50% in order to be considered a legitimate size change.

   b. For defects (illuminated with normal edge lighting) with estimated radiometric size of 50 um above, we can size with at most $\pm$ 20% accuracy. For these sites, the size over time should have to increase by >20% in order to be considered a legitimate size change.

3. Size Change (maximum – minimum). Maximum size of the defect site is defined as the biggest size of the defect site in the last 3 observations; conversely, minimum size of the defect site is defined as the smallest size anytime in the defect history except for the last 3 observations. This is to restrict the possible impact of outliers.

The following definitions are now being implemented in rules development especially in data mining efforts:

Has-Grown: A site is defined as “Has-Grown” if its maximum estimated size (over last 3 observation) is substantially larger than its minimum size (over entire history), i.e. >50% for minimal size $\leq$50 um, >20% for minimal size >50 um.

Growing: A site is defined is “Growing” if its maximum estimated size (over last 3 observation) is substantially larger than its minimum size over last 6 observation (>50% for minimal size $\leq$50 um, >20% for minimal size >50 um).

Implementation of Damage Rules in the Damage Calculator

To calculate new initiations on an optic, the Damage Calculator (DC) must have knowledge of the fluence distribution of the proposed shot, as well as knowledge of the fluence history of that particular optic in question. This optic-specific DIE fluence information must be tracked for each surface and at each of the three harmonics of the fundamental fluence. A “Max-of-n” (n represents shot number, also “MaxN”) fluence map, $\Phi_{max}(x,y)$, is used to record this information.

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Such a map is illustrated in Figure 2. Thus, each surface of each optic has associated with it a Max-of-n fluence map such that each point stores the maximum damage initiation equivalent fluence that each spatial point has seen to date. For each shot, the DC uses LPOM-generated fluence maps of the proposed shot to update the Max-of-n fluence map to $\Phi^*_{max}(x,y)$. The number of new initiations ν for the proposed shot is then given by:

$$\nu = \iint \rho[\Phi^*_{max}(x,y)]dxdy - \iint \rho[\Phi_{max}(x,y)]dxdy,$$

where $\rho(\Phi)$ is the rule for damage density as a function of fluence for that surface.

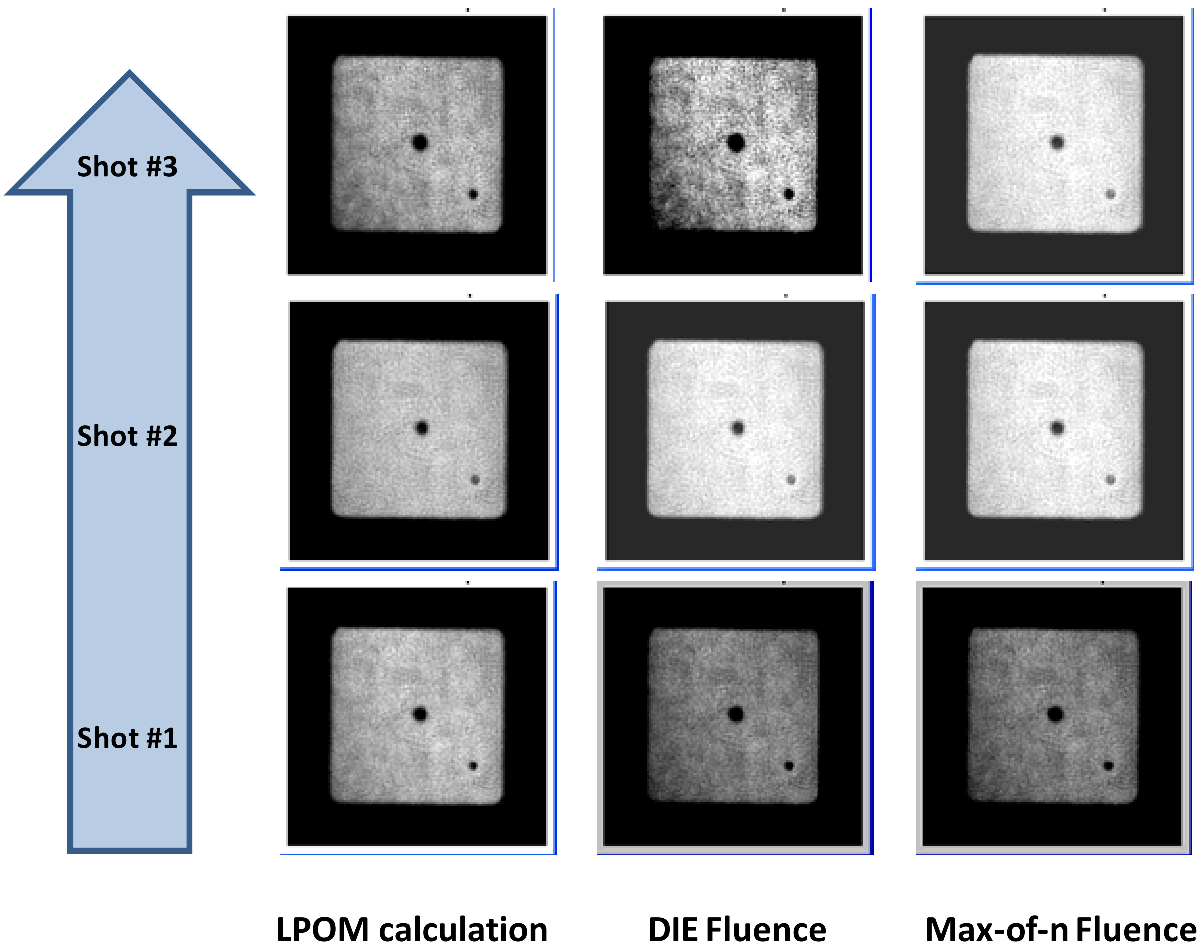

Figure 2) Illustration of Max-of-n fluence maps. Beam profiles are about 34cm x 34 cm, and show two blocker “holes”.

The Damage Calculator looks forward in the shot plan to calculate the Exchange CDF, which is the probability that on or before the n^{th} shot the optic will need to be exchanged due to damage growth. Two approaches to calculating the Exchange CDF were studied: Monte Carlo simulations and closed-form algebraic solutions. Monte Carlo methods are robust with any form of damage rules, but can be slower (up to 1000 times) than closed-form solutions which are not available for all forms of damage rules. An optic needs to be exchanged after the maximum

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number of blockers have been applied. Blockers are applied to individual growing sites after they reach a maximum size. Thus, the Exchange CDF can be written:

Exchange CDF(shot n) = 1 – Π_j [1 - Flaw Exchange CDF (j^{th} flaw, shot n)] ,

where the Flaw Exchange CDF is the probability that a site will grow at the 95^{th} percentile level on the next shot and exceed the maximum allowed flaw size. Monte Carlo methods are used to evolve each flaw's size distribution according to the growth rules. Each rule is formulated into a CDF(M) for the distribution of the magnitude of the growth multiplier M = new_size/old_size on each shot. Inverting this CDF distribution gives $CDF^{-1}(x)$. The flaw size distribution is evolved upon multiplication with $CDF^{-1}(u)$, where u is randomly picked from a uniform distribution on the interval [0,1]. An ensemble of 1000 points is sufficient to track the flaw size distribution while maintaining reasonable calculation times.

Figure 3 shows the predicted versus actual exchange for a shot campaign on NIF. Both Monte Carlo and closed-form solutions are shown to be in good agreement. The predicted exchange (50% probability) was on the 35^{th} shot, whereas the actual exchange in the campaign occurred on the 34^{th} shot. This data validates both the CDF methodology and the rules used to make the predictions.

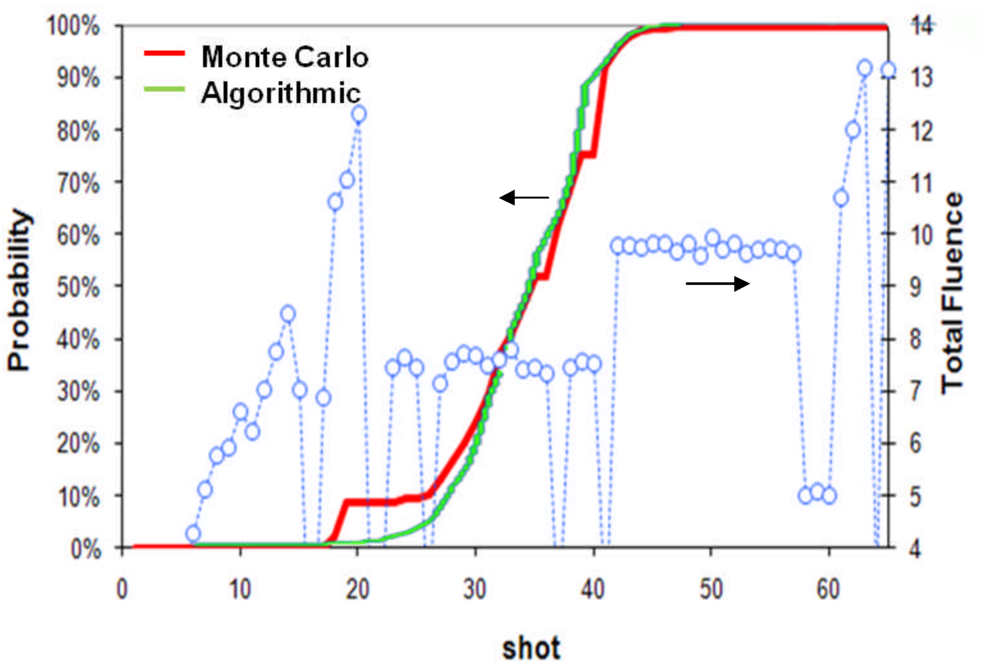

Figure 3) Optic exchange is predicted when the Optic Exchange CDF reaches 50% probability.

The accuracy of the Flaw Exchange CDF predictions has been tested against actual NIF data with good results. Figure 4 shows predicted flaw size versus the FODI observed size for a 15-

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shot campaign on NIF following 292 damage sites on a debris shield, where the maximum allowed size is 12 mm.

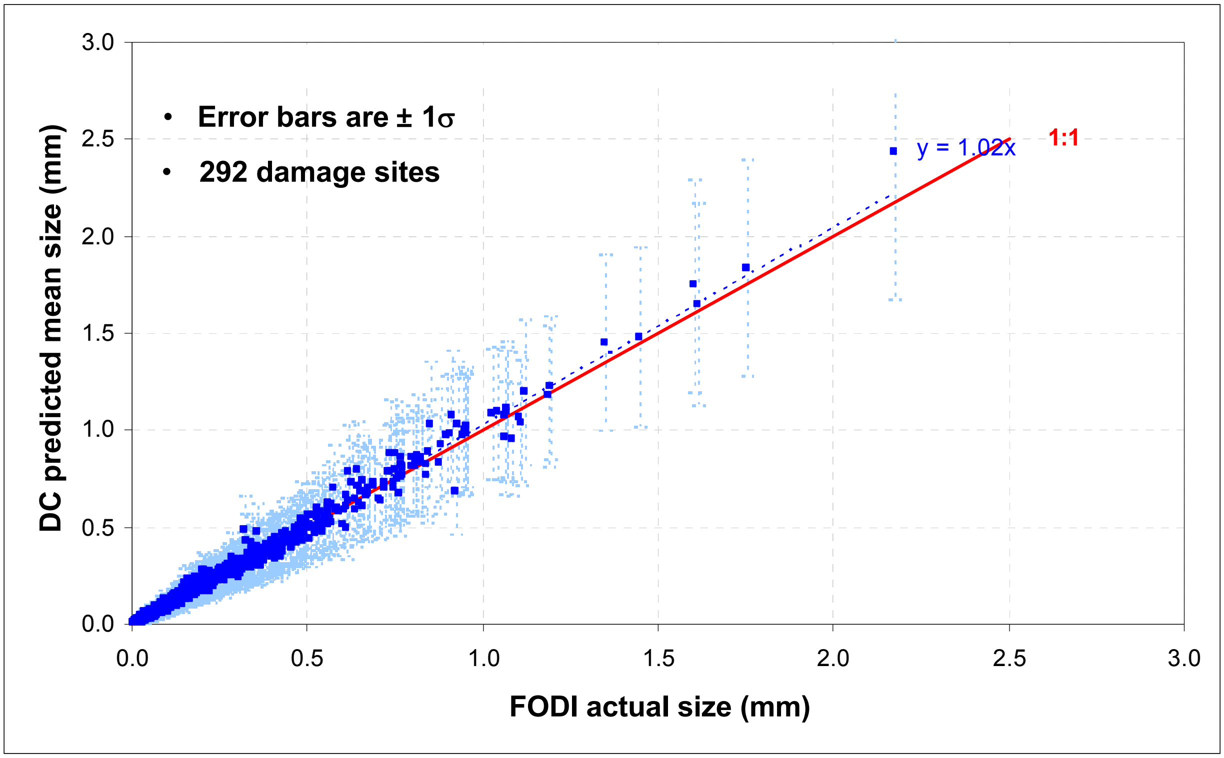

Figure 4) The Damage Calculator (DC) predicted mean size for 292 growing sites over 15 shots agrees well with the actual size radiometrically determined by FODI.

OpticsX: a platform for new rule and algorithm development

OpticsX is a prototype code developed as an on-demand, flexible, and rigorous model for evaluating optics lifetime as function of laser parameters and rule-sets, without the need to interact with production databases. OpticsX allows testing of new, more sophisticated rules and algorithms prior to implementation in the Damage Calculator. It has the ability to evaluate optic damage performance for an arbitrary set of inputs. OpticsX was developed using Matlab with its many advanced toolboxes (such as statistics, and in the near future, data mining) to perform Monte Carlo simulation for predictive modeling of damage evaluation on full scale, online and offline data. The algorithm is comprised of three main subroutines, one to compute initiations, one to compute growth using the initiations, and one to analyze results for pull criterions. The initiation subroutine uses optics pedigree based damage density rules and calculated Max-of-n fluence probability densities (along with DIE scaling) using empirically derived results from online analysis. It outputs accumulated number of initiations for each surface of an optic after each shot which is fed into the growth subroutine. Since the current growth rules are found to be stochastic, the growth subroutine uses the Monte Carlo simulation to predict how each initiation site will grow. The growth rules routine calculates the growth fluence which has both

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wavelength and pulse-shape dependence. Assuming that the defects are usually initiated at hotter spots of the beam, it is reasonable to assume that the sites will be grown at higher than normal fluences. These sites are grown at fluence at +1 standard deviation (spatial contrast) of the beam-averaged fluence. The final subroutine analyzes the result with respect to when the optics needs to be pulled and how many potential sites need to be mitigated at each optic.

The result of the simulation is shown in Figure 5. It consists of 6 graphs displaying results from the various subroutines. The first graph shows the optics pedigree-based damage density rules used in the calculation. The second graph (top middle) shows the fluence distribution of the shot chosen; for this simulation it was the 1.8 MJ ignition pulse, and includes the calculated Max-of-n distribution for the number of shots simulated (N=100 for this simulation). The third graph shows pulse shape and the cutoff beam intensity in order to calculate effective fluence (fluence of pulses after 0.3 GW/cm^2 is achieved). The fourth graph displays the number of initiations (and the exit initiations) as a function of shots the simulation projects. The fifth graph shows the empirical pull-shot cumulated density function (CDF) from the 1000 Monte Carlo simulations for both maximal size as well as the maximal obscuration limit. The final graph shows the ensemble size CDF (size for all the sites from all 1000 Monte Carlo simulation) if those artificial 1000 optics were all pulled at the same time for mitigation.

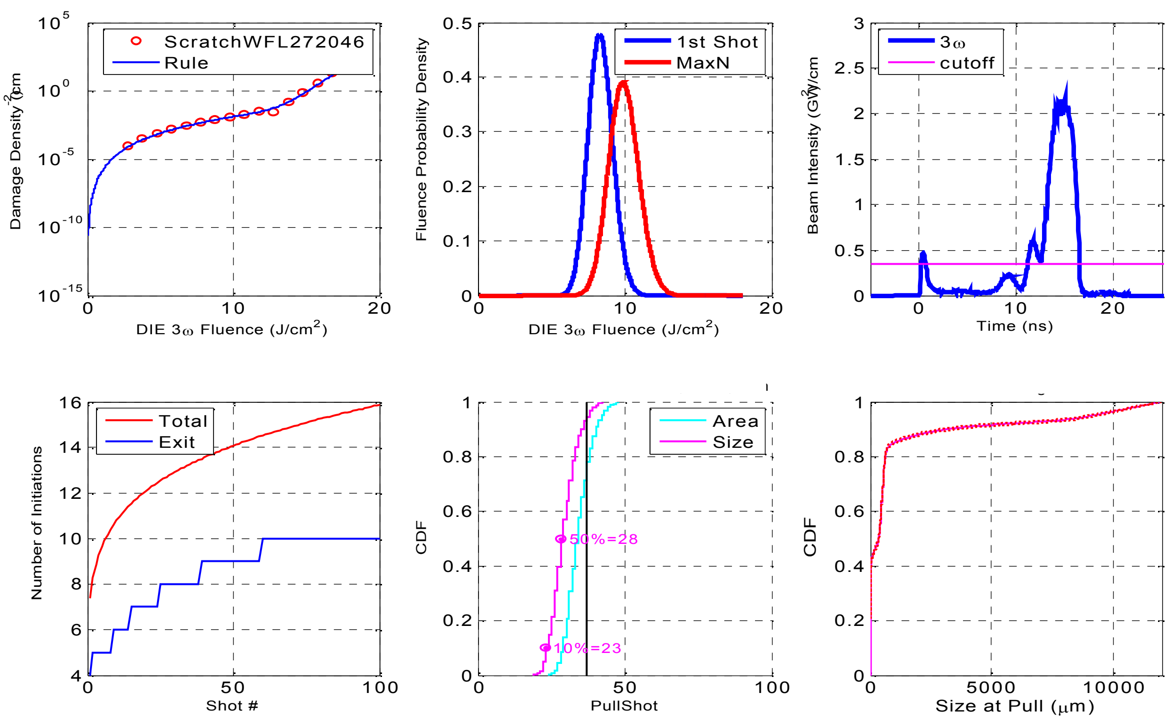

Figure 5) OpticsX result display for lifetime simulation of WFL optic running at 1.8 MJ campaign.

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Shot Planning and Analysis Tool (SPLAT) for managing the optics exchange loop

The damage rules, strategies, and predictive algorithms discussed in this paper are now embodied in a web-based tool-set known as SPLAT (Shot Planning and Analysis Tool), which became available to NIF operations in 2010. An example screen shot is shown in Figure 6. Detailed analysis of the SPLAT system will be the subject of future publications. The SPLAT architecture, shown in Figures 7 and 8 for reference, demonstrates the central role of the Damage Calculator.

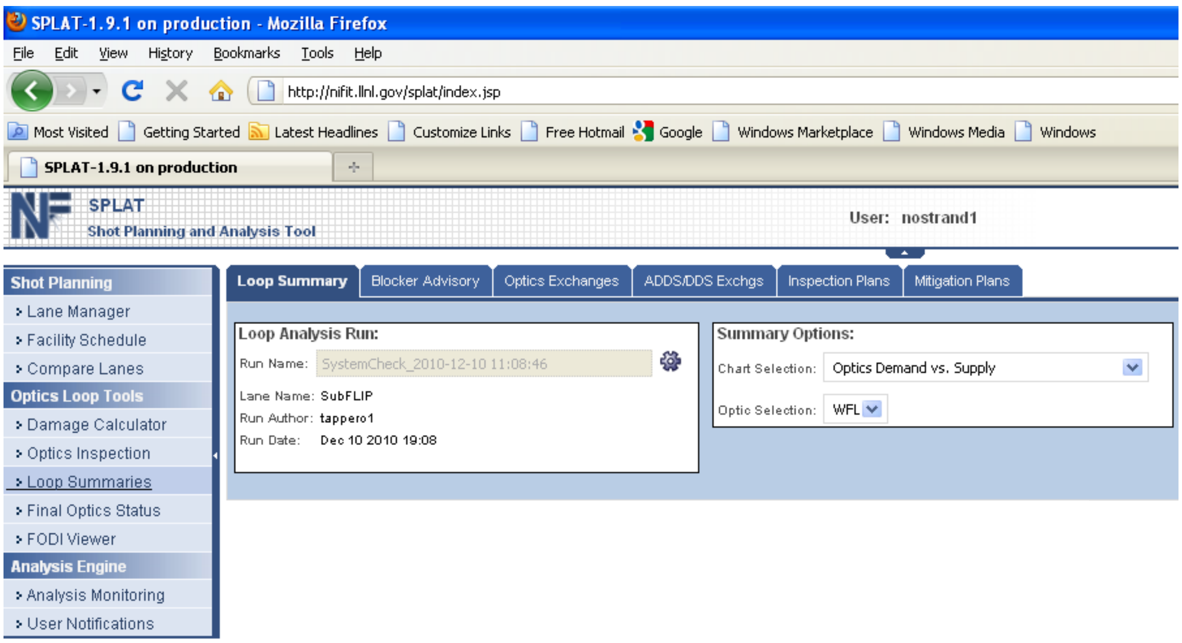

Figure 6) Example screen showing current production capabilities of SPLAT tools.

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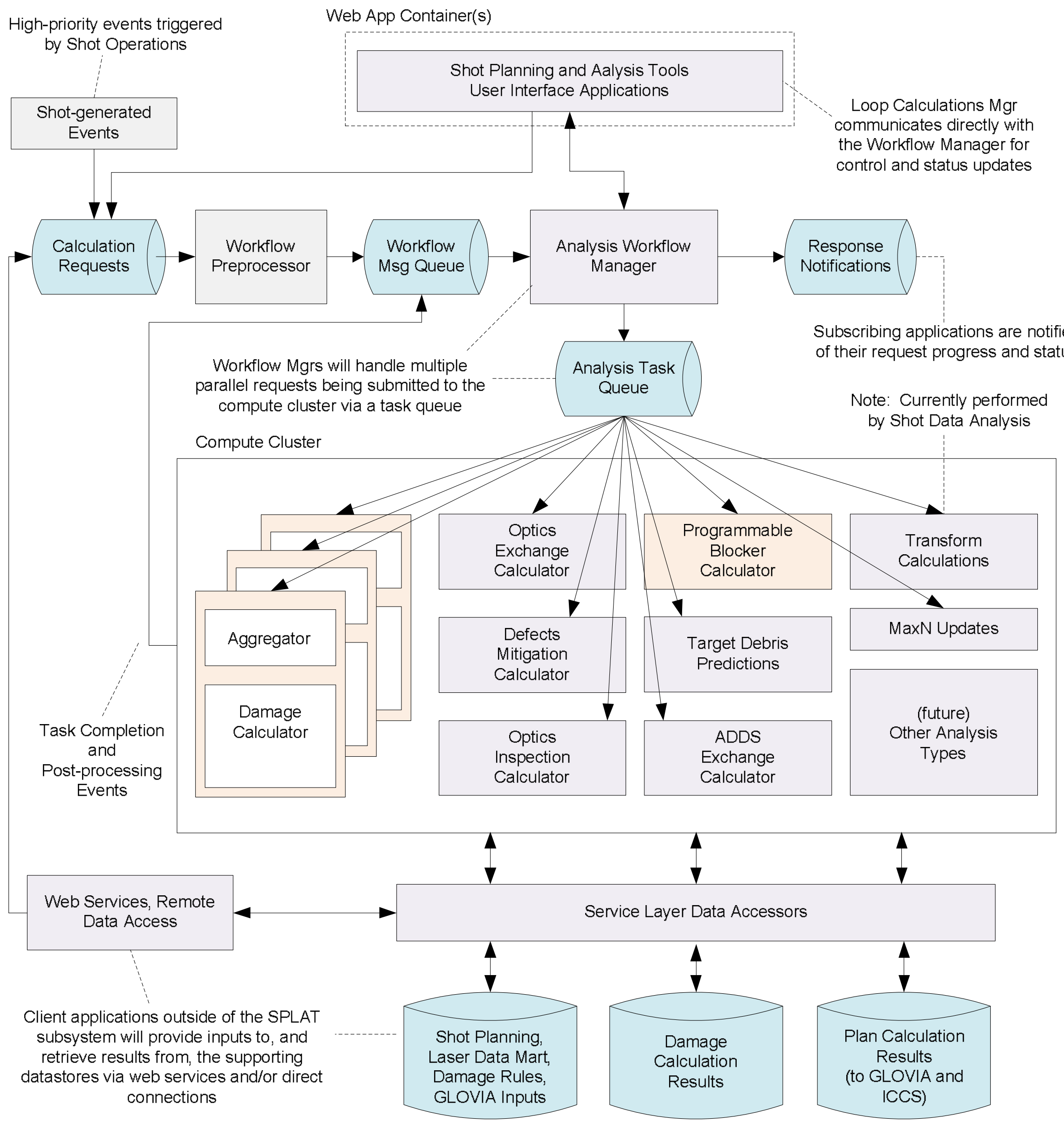

Figure 7) High-level diagram shows the SPLAT Architecture represented in a standard multi-tiered format depicting the separation between the presentation, applications, and datastores layers.

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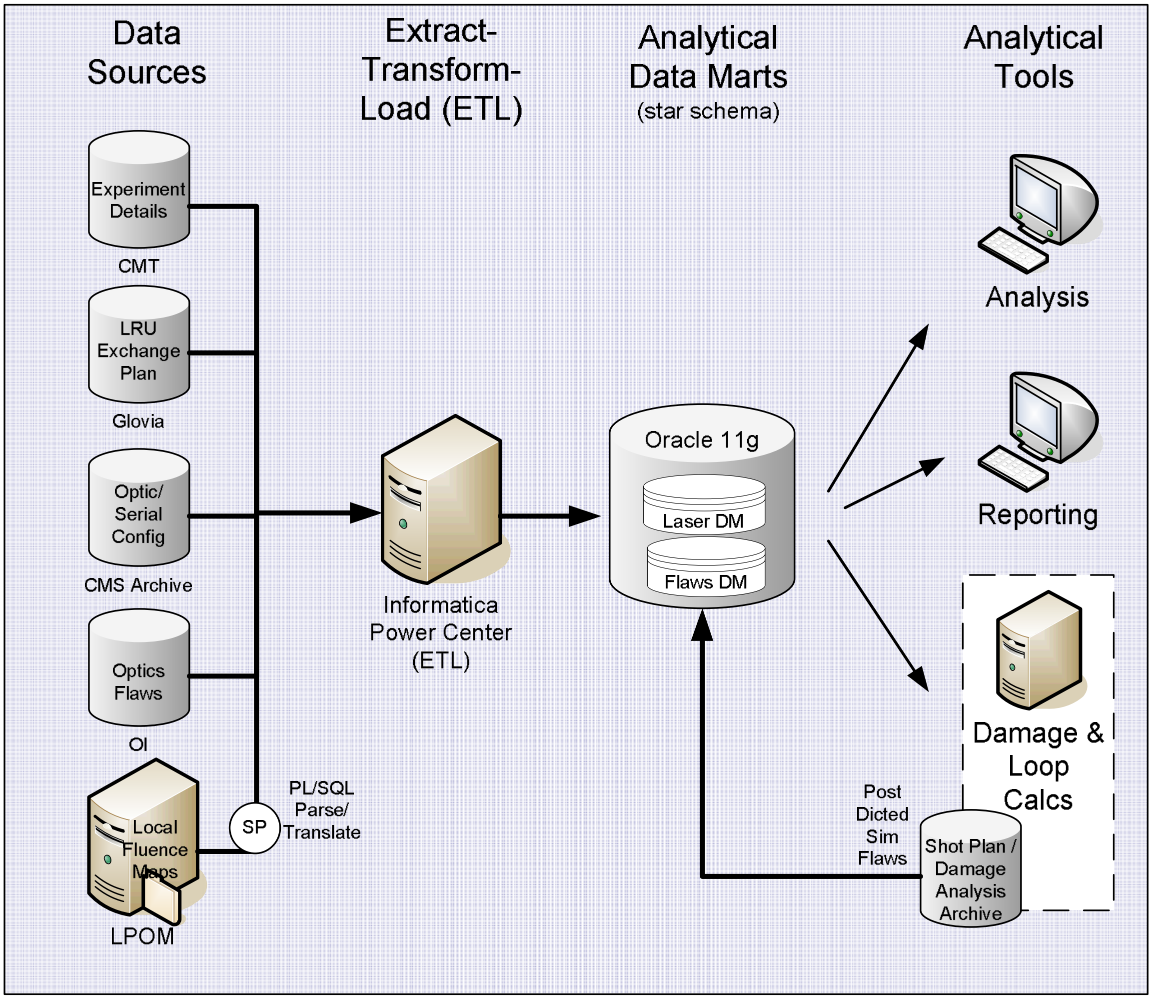

Figure 8) Conceptual diagram to show to role of ETL and the analytical data marts in the SPLAT architecture. The analytical data marts provide a source for SPLAT damage calculation inputs.

Summary

We have developed predictive tools necessary for operating a fusion-class laser to its full potential. These “Loop Tools” , with the Damage Calculator at their core, allow the strategy of the “Loop Diagram” to be implemented in the production environment of ICF-class lasers.

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