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

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May 13, 2016

Pacific Rim Laser Damage 2016
Yokohama, Japan
May 17, 2016 through May 20, 2016

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Talk Outline

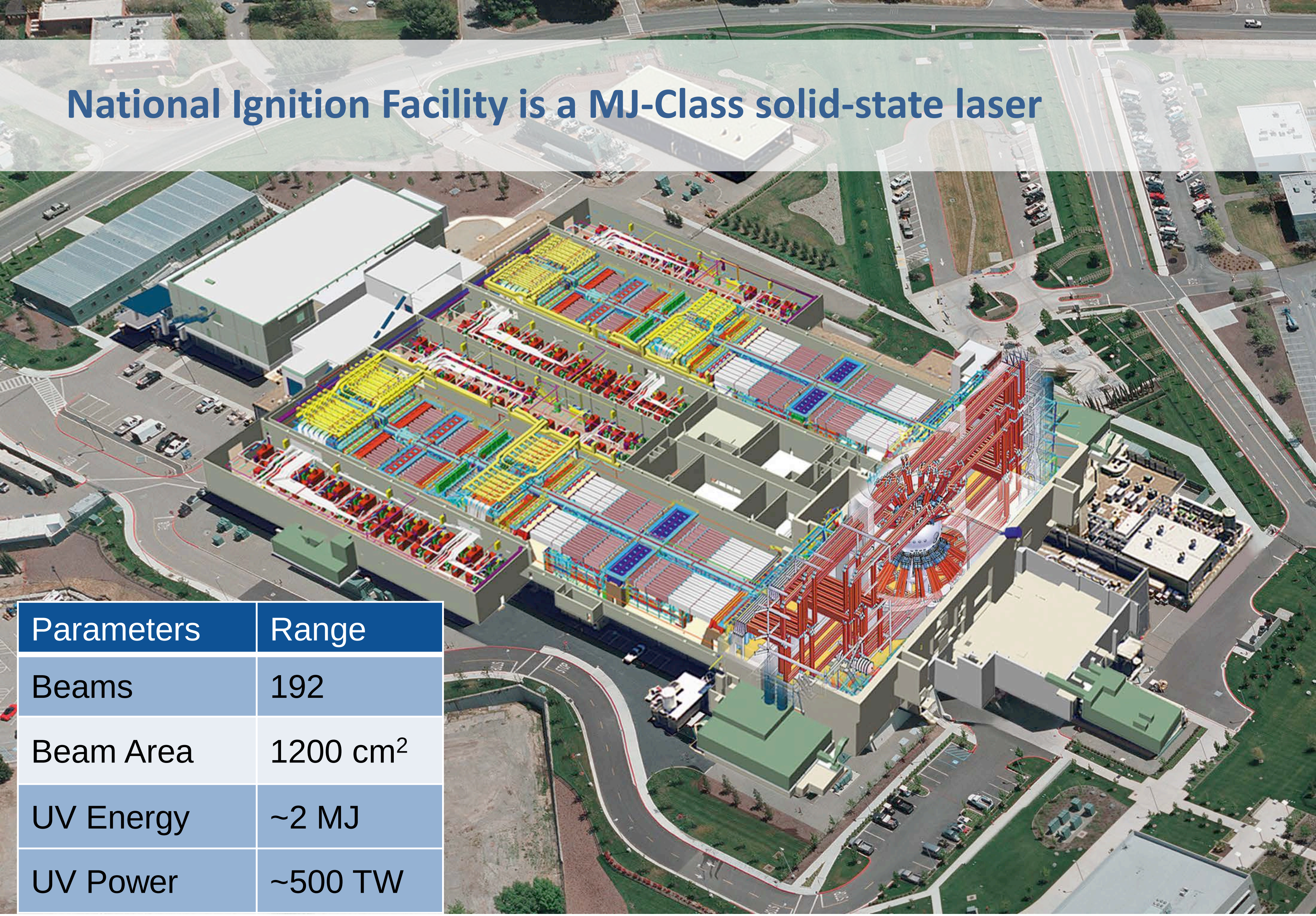
- Introduction
- NIF & Online Damage
- NIF Optics Loop
- Damage Model
- Simulation Results
- Conclusion

Introduction

- NIF is the world's most energetic laser, delivering up to 2.0 MJ at 351 nm with its 192 beams
- NIF uses some of the best damage-resistant optics in the world and uses optics loop[1] to manage laser-induced damage in optics
- How long an optic lasts (i.e. lifetime) depends on damage initiation and growth
- Over the past 5+ years, thousands of optics have been cycle through this process and it is the primary cost of running the facility. We have build a damage model that is able to predict the rate of optics usage.

1. Spaeth et. al., FST 2016

National Ignition Facility is a MJ-Class solid-state laser



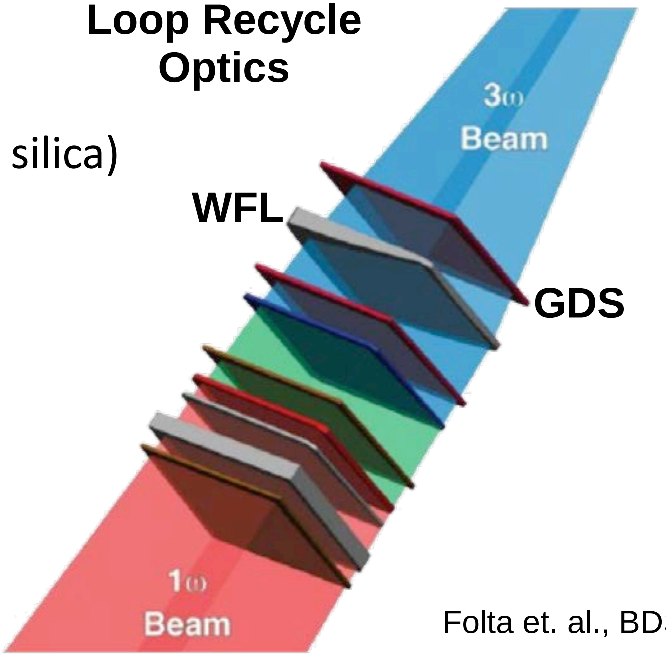
Parameters	Range
Beams	192
Beam Area	1200 cm^2
UV Energy	~2 MJ
UV Power	~500 TW

NIF operating fluence is limited by damage to the UV optics

- NIF is a Nd-doped phosphate glass laser running at 1053 nm that it is frequency-tripled to 351 nm just before entering the target chamber. The most at risk optics are the final optics that are exposed to the UV light.

- The Wedge focusing lens (WFL) and
  Grating debris shield (GDS)
  are the final optics (both made from fused silica)

- These two optics are the
  focus of NIF's optic's loop



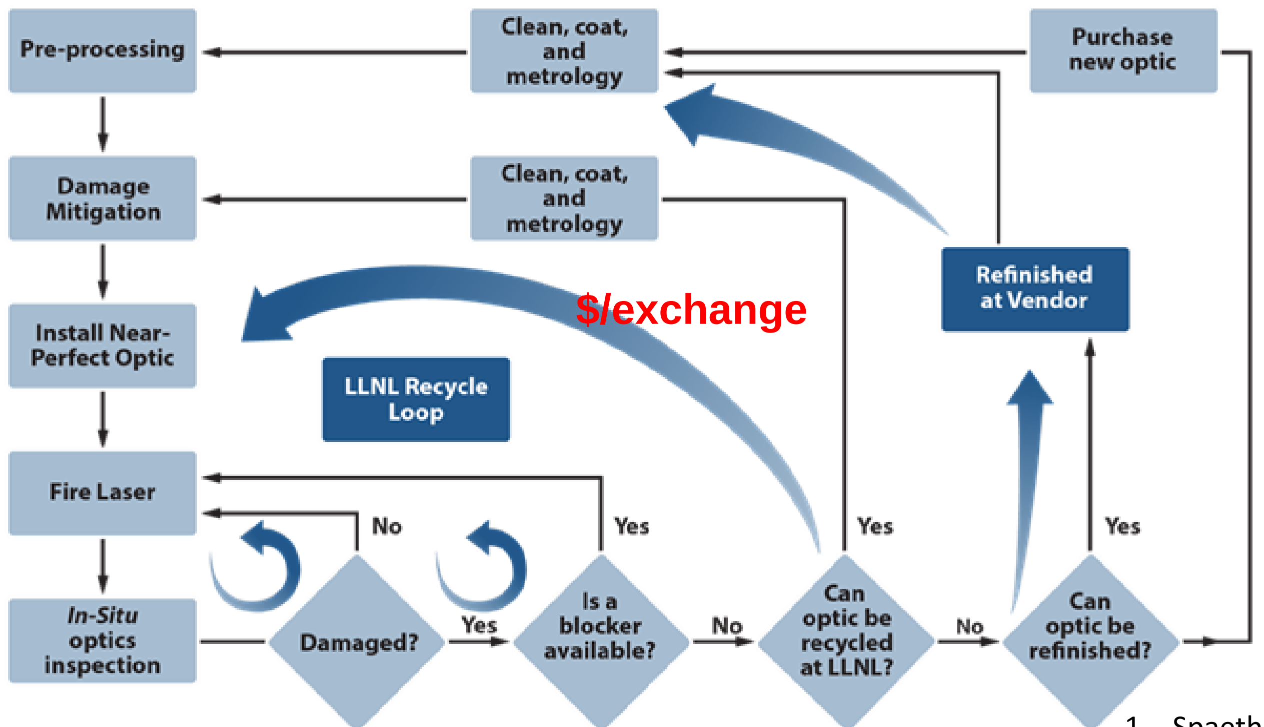
Folta et. al., BDS 2013

We will simulate the optics usage of the two final UV optics

NIF loop strategy allows NIF to run the laser at the laser-induced damage regime

- The **NIF loop strategy**[19] consists of recycling optics to repair the damage sites, thus allowing a single optic to be used **multiple times before it needs to be refinished or replaced**.

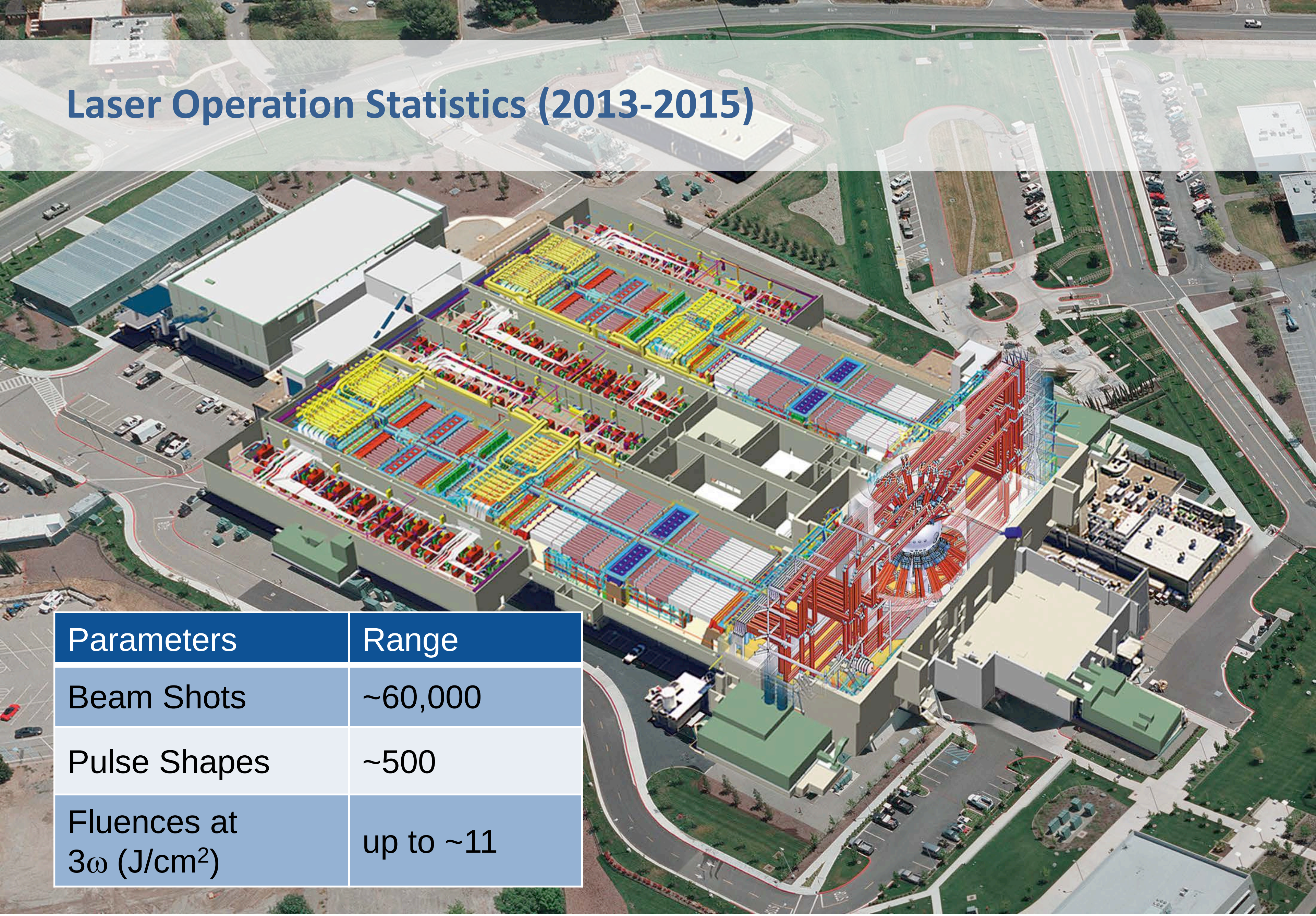
$/site



1. Spaeth et. al., FST 2016

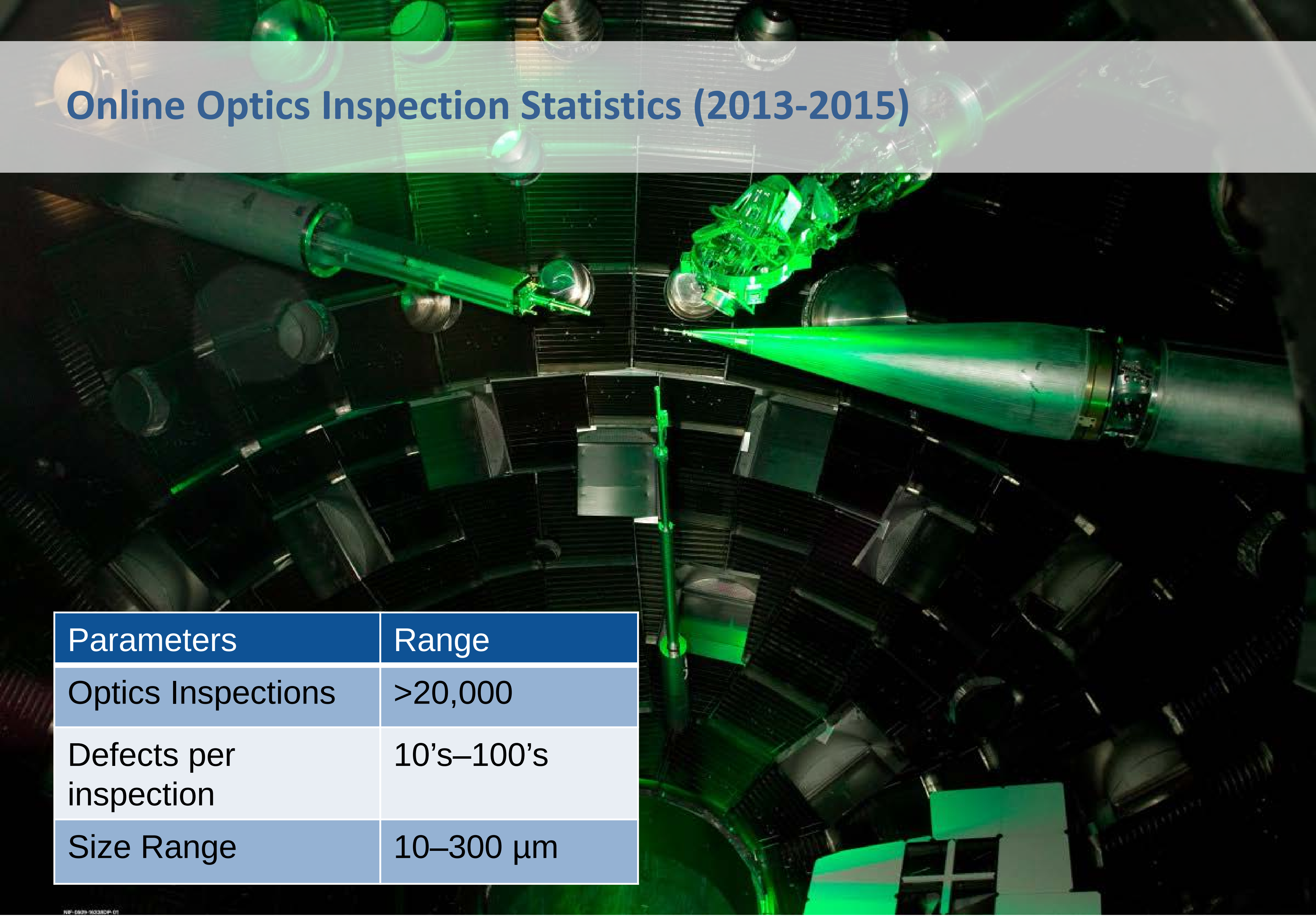
Optics exchange is the dominant cost driver for the Optics Loop

Laser Operation Statistics (2013-2015)



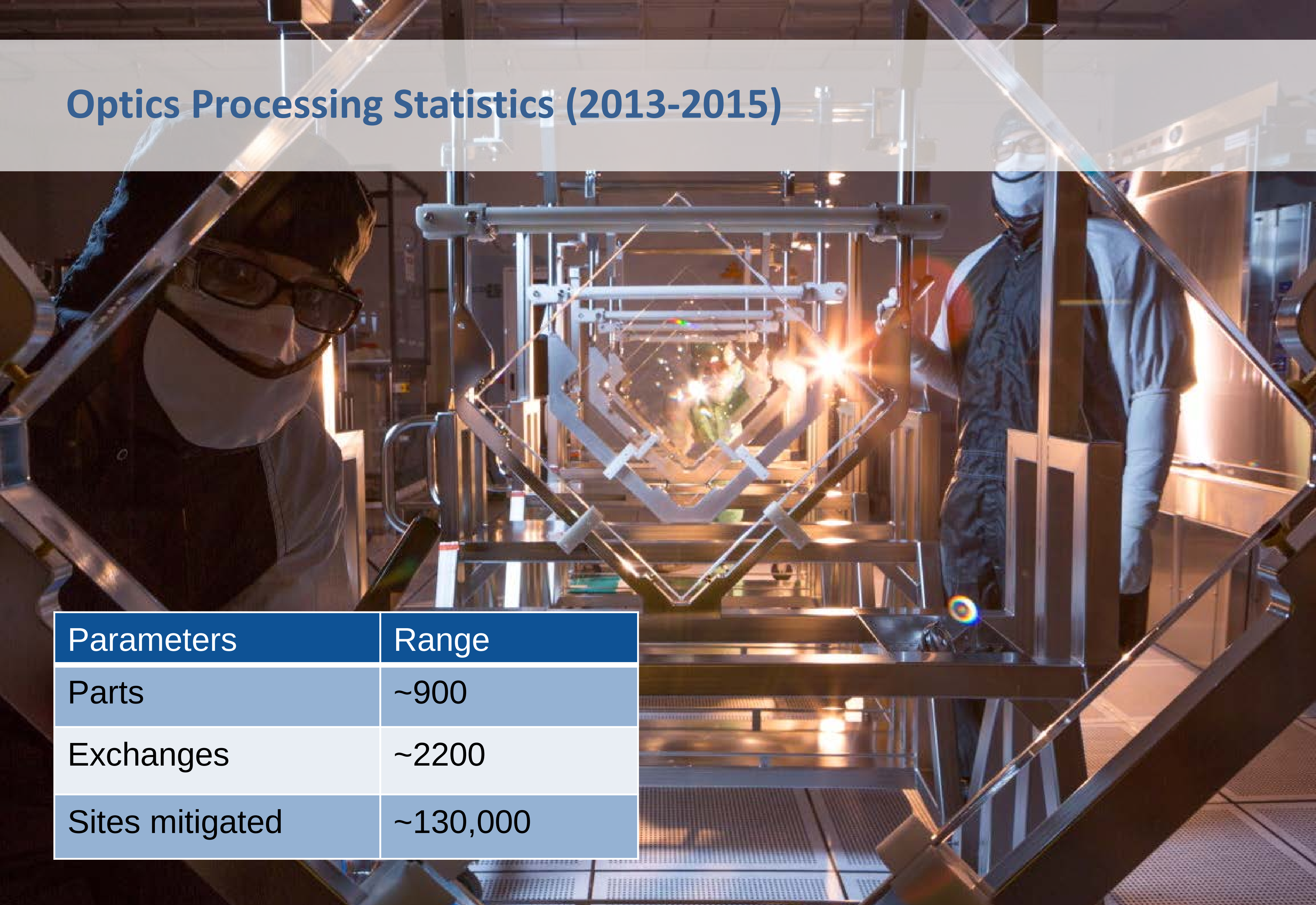
Parameters	Range
Beam Shots	~60,000
Pulse Shapes	~500
Fluences at 3ω (J/cm^2)	up to ~11

Online Optics Inspection Statistics (2013-2015)



Parameters	Range
Optics Inspections	>20,000
Defects per inspection	10’s–100’s
Size Range	10–300 µm

Optics Processing Statistics (2013-2015)



Parameters	Range
Parts	~900
Exchanges	~2200
Sites mitigated	~130,000

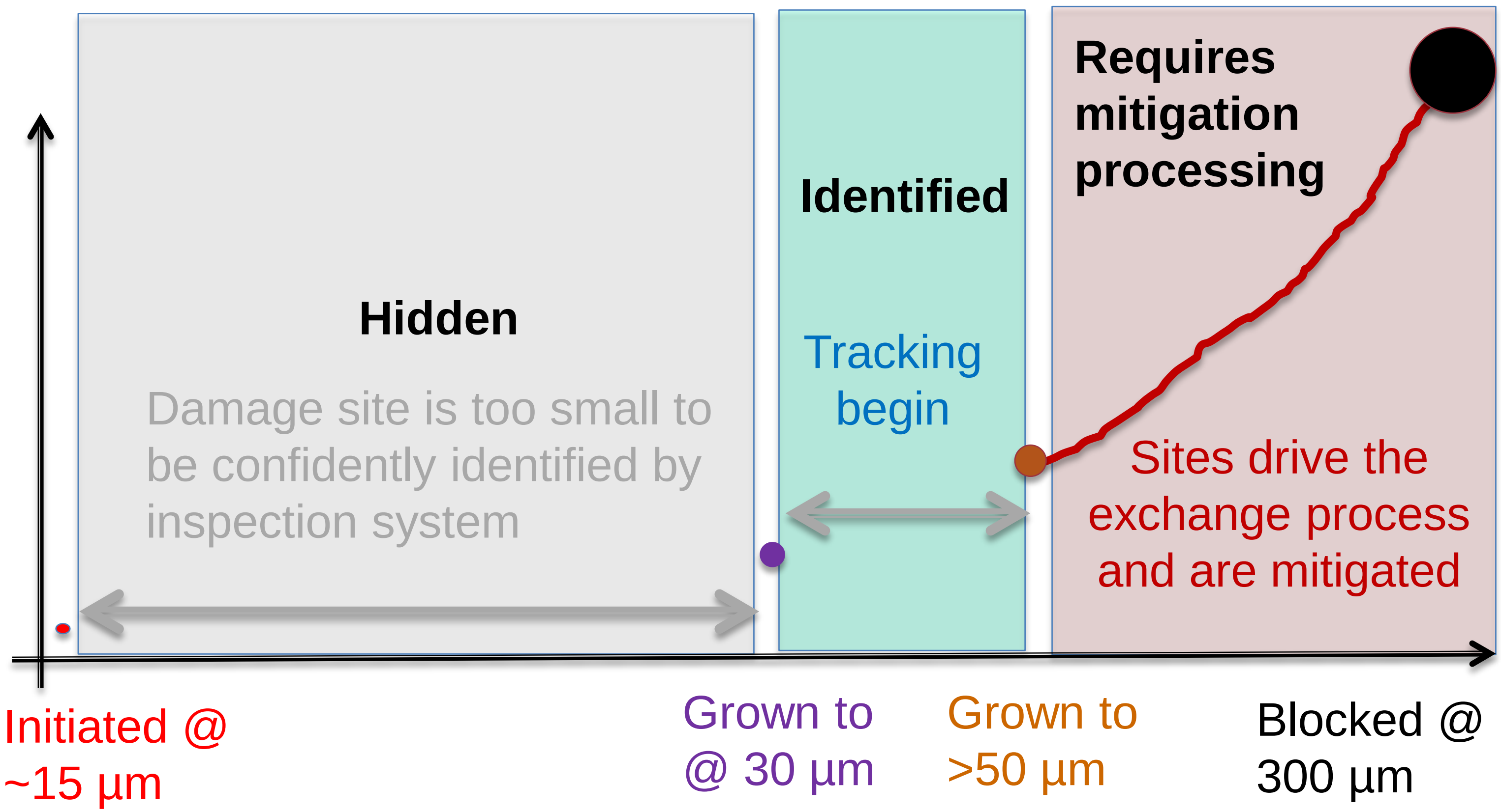
Number of damage sites does play a role in optics lifetime but not as very strong (~ log(N))

- Optic usage is due to laser-induced damage initiation and growth but because of how we run the laser system, the optic usage is driven by damage growth
- Damage sites are block when they reach ~300 µm, there are fixed number of blockers available per quad (4 beams, 8 optics)
- The optic then exchange once the blockers are used up (~3-5/ optic). There are usually many more damage sites (N) than blockers available.

D_0 (µm)	N=10 Sites (shots till exchange)	N=100 Sites (shots till exchange)	Rate increase
15	**1250**	**375**	3.3x
25	**500**	**130**	3.8x
35	**110**	**80**	1.4x

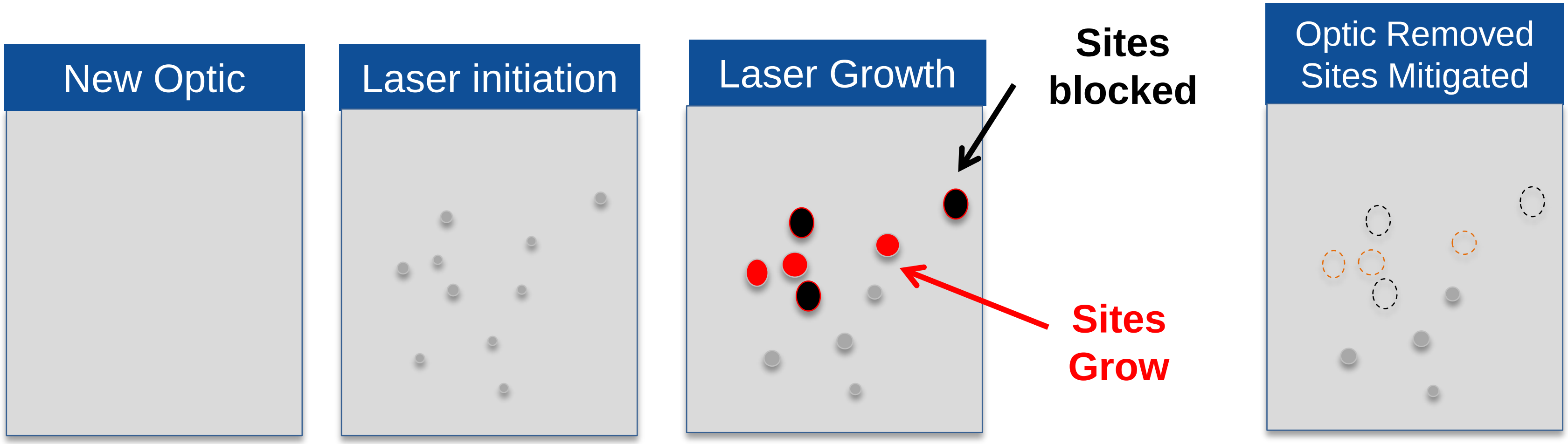
Number of damage sites does playa role but is not a strong indicator of optics lifetime(lifetime ~ log(N))

- Our online inspection system (FODI) have limited capability in tracking damage sites over its lifetime



Laser-induced damage and optics usage

- Optic usage is due directly to laser-induced damage initiation and growth but because of how we run the laser system, the optic usage is driven by damage growth



- The optics are exchange once the number of blockers are exhausted
- The number of available blockers are share with 4 adjacent beams (8 optics)
- Residual damage sites can become the seed for driving the next exchange

Fused Silica Growth Model

- Model is developed from offline experimental facility[1]

$$\boxed{D_n = D_{n-1} \times e^{\eta \cdot \alpha}}$$

D: diameter
n: shot index

- η and α are random variables that governs the probability of growth and growth rate as a function of laser parameters

- Prediction is based on Monte-Carlo simulation of these random processes[2,3]
  - Probability of growth, η which obeys the Binomial distribution
  - Distribution of exponential growth rate, α which obeys Weibull distribution

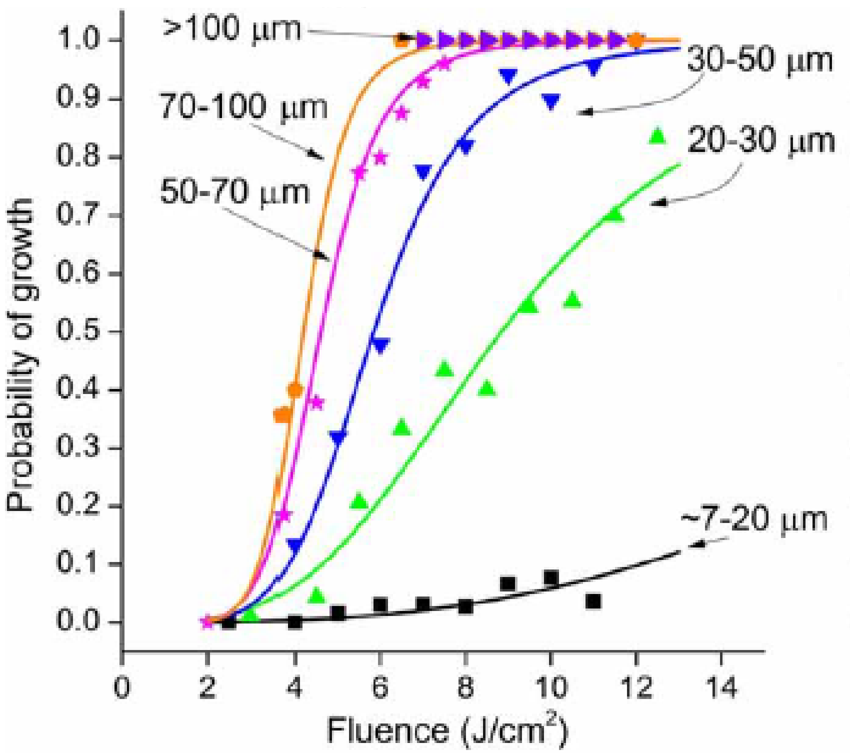
1. Norton, Negres, Carr et. al.
2. Liao., OE 2012
3. Negres, OE 2014

Probability of Growth (η) follows Binomial distribution

- Derived probability of growth from offline experimental data
- Is a function of laser fluence and intensity as well as damage size
- Obeys Binomial distribution

$$\eta = C(m, X) \times p^X \times (1-p)^{m-X}$$

C: binomial coeff.
X: number of success
m: number of trails
p: probability of success



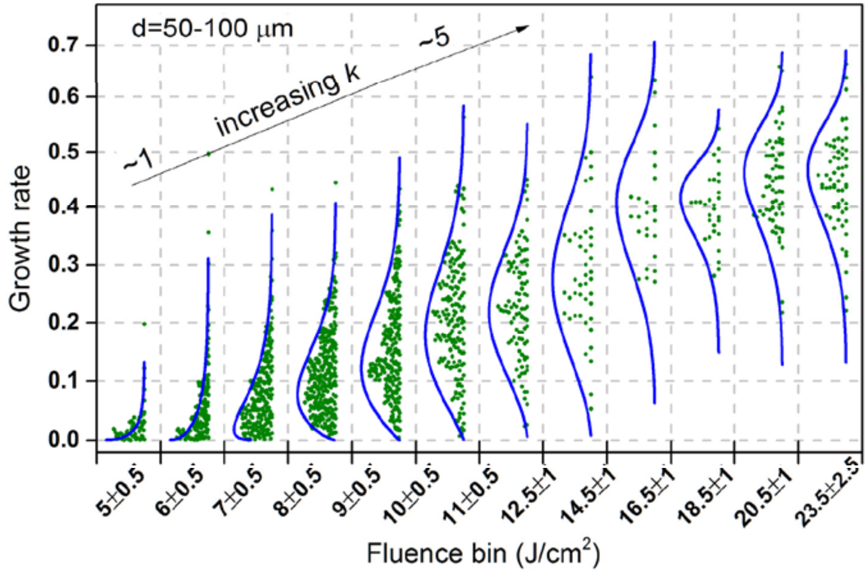
Negres et. al., Opt. Exp. 2012

Growth rate (α) follows Weibull distribution

- Derived growth distribution from offline experimental data
- Is a function of laser fluence and intensity as well as damage size
- Obeys Weibull distribution

$$\boxed{\alpha = (\boldsymbol{k}/\lambda) \times \left(\frac{\alpha}{\lambda}\right)^{(\boldsymbol{k}-\mathbf{1})} \times \boldsymbol{e}^{-\left(\frac{\alpha}{\lambda}\right)^{\boldsymbol{k}}}}$$

λ: Weibull scale
$\boldsymbol{k}$: Weibull shape



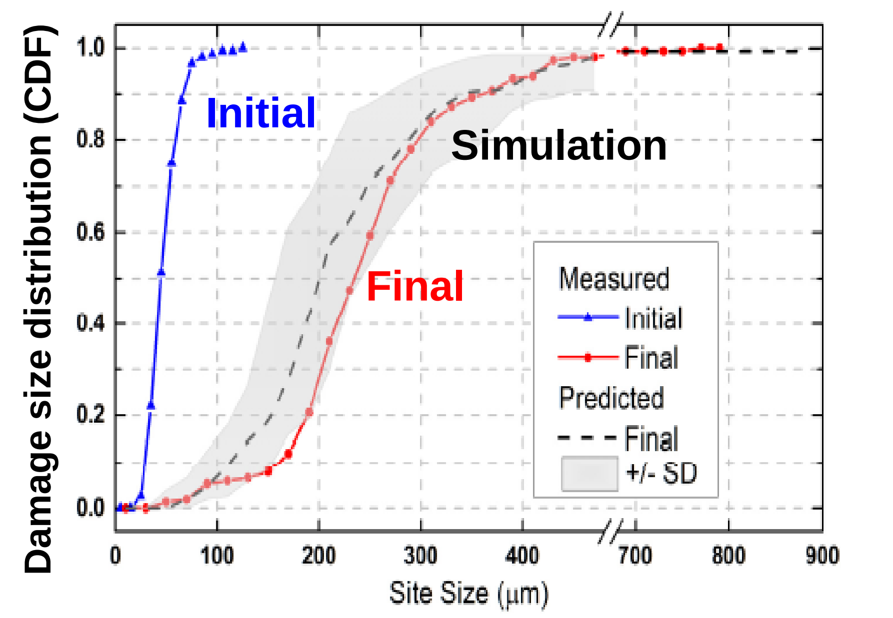
Negres et. al., Opt. Exp. 2014

We have tested the mean as well as the shape of the growth distribution

Damage model have been validated with offline data

- Offline Experiment
  - Pre-Initiated damage sites
  - 150 sites (30-100 µm)
  - 4-20 shots
  - Gaussian shape pulse
  - Usually same fluence sequence
  - Limited testing area (~10 cm^2)
- Online data (2012-2015)
  - ~60,000 beam shots
  - 500 pulse shapes
  - 1.5 million square meter

Offline Growth Experiment & Simulation



10’s cm^2 and limited Shots (4- 20)

Negres et. al., Opt. Exp. 2014

Damage model have been validated with limited data set (one shot, full 192 beams)

- The most accurate online growth data consists of when optics inspection was perform directly before and after the shot (i.e. single-shot growth data)
- These data are infrequent but it gives the best feedback regarding the accuracy of the damage model

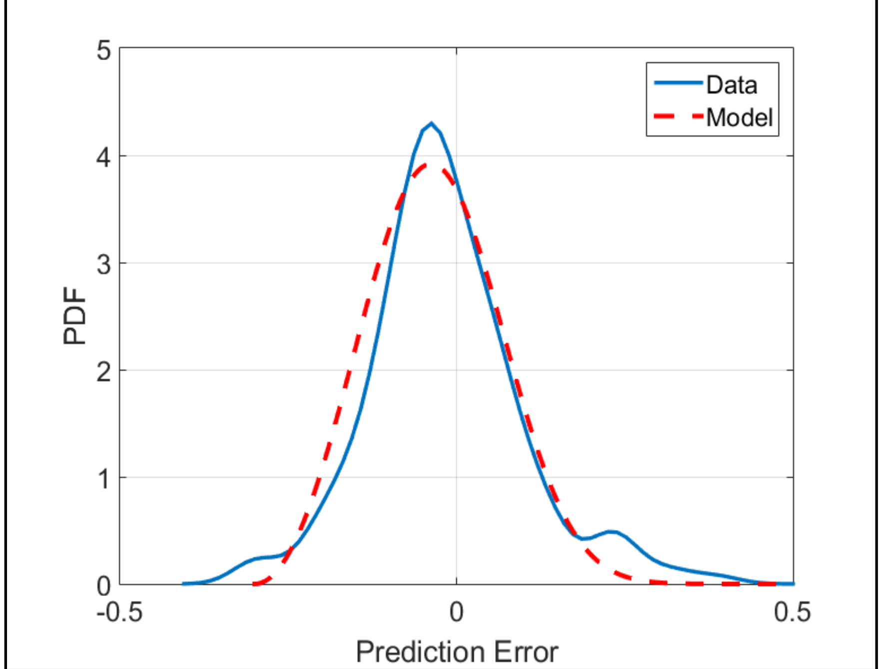
Shot ID	Campaign	Beams	ϕ_{3w}	Sites
N141028-003	H_Cval_2DConA_3ShAs	192	~8	33,000

We will use this data to spot check the validity of the growth model

Online data shows that the growth expectation value is consistent with the model

- For each beamline, we have a measured average growth rate and a predicted growth rate
- Prediction error is the difference between the measured and the calculated expected value. It peaks close to 0, this implies that calculated α is approx. correct.
- Overlaying the full α Weibull distribution model shows that the range of variation is consistent with the shape of the distribution

Measured-Predict per Beam



Difference centers near 0

The range of prediction error is consistent with the Weibull distribution

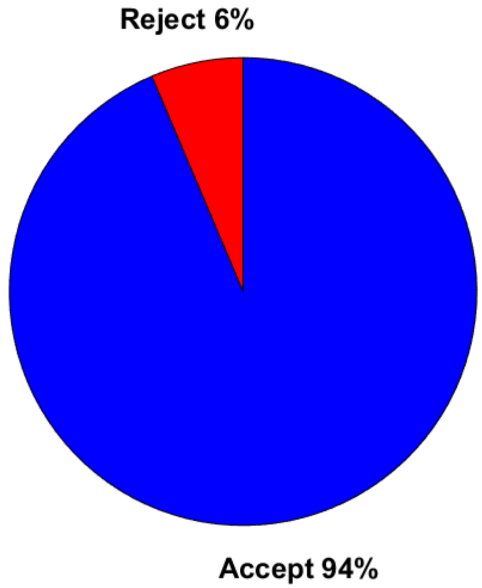
Online data shows that the growth Weibull shape is consistent with the model

We can also perform hypothesis test to determine whether:

1. Each beamline data could have come from Weibull distribution via. Anderson-Darling test

2. Each beamline data matches the mean and variance via. Chi-Square goodness of fit test

Distribution Shape Verification



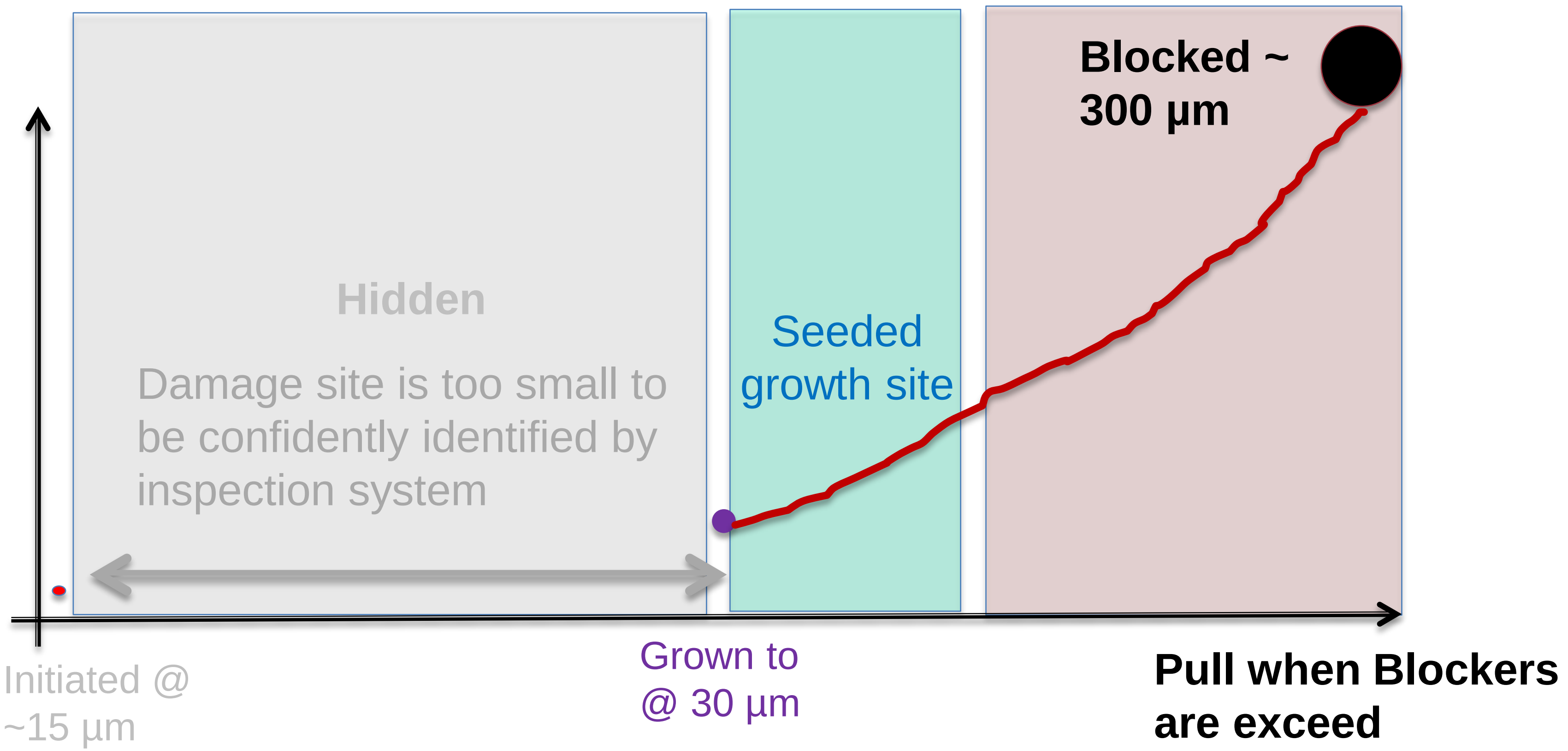
47 beamlines with enough data tested

Full NIF simulation setup

- Shot sequence for each of 192 beamline have been separated into each beamline and each optic (WFL, GDS) for simulation input
- Each beamline has a start and end date which coincides with first optic install in 2013 and last optic removed in spring 2015
- Each optic installed is "seeded" with damage sites that are ~30 µm (these are sites that were initiated in previous installed but not large enough to be mitigated, i.e. <50 µm)
- These sites are grown and blocked accordingly. When blocker limited is reached (5/optic), the optic is removed and a new optic is install

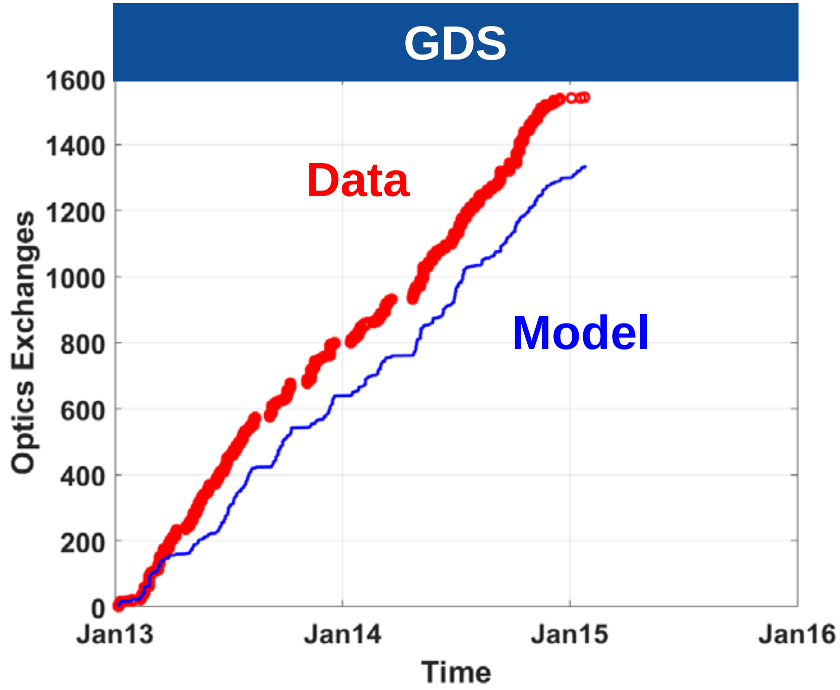
Full NIF Loop Simulation

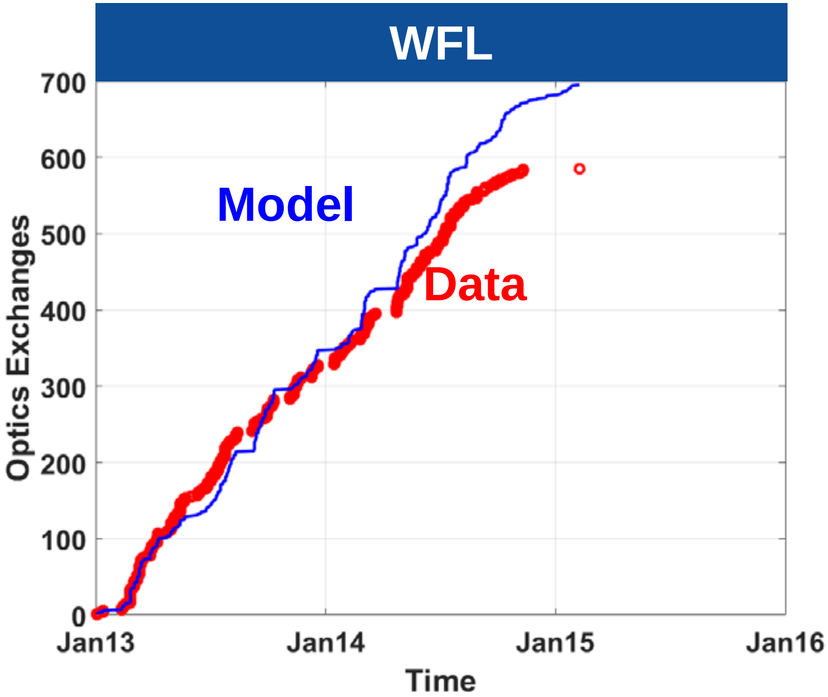
- Seeded optics with damage sites that are consistent with online observation and then pull optic when blockers are exhausted



Simulation result by optic type

- Accumulated exchange for each optic type is within ~15% of data
- Under predict for GDS, over predict for WFL

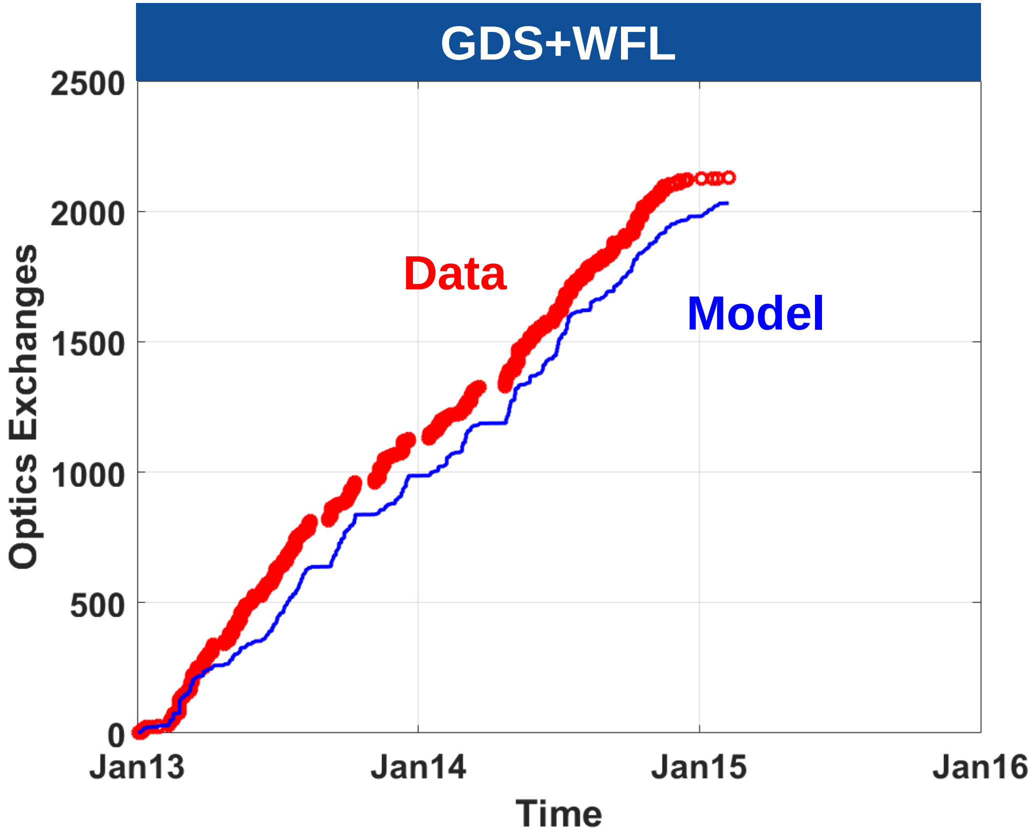




Simulation results tracks with actual exchanges over time

Simulation result with all optics

- Accumulated optics exchange (WFL + GDS) is within 5% of data. This is because WFL and GDS shared the same blocker.



Summary

- NIF is the world's most energetic laser and it routinely runs at energy levels above the damage threshold.
- NIF uses a combination of beam blockers and damage site mitigation technology (Optics Loop) to meet the laser performance as well as stay on schedule and on budget.
- Currently, the Optics Loop is primarily driven by damage growth and we have developed a model to predict optics usage.
- We are able to predict the exchange rates for NIF (2012-12015, ~60,000 shots) within 95% accuracy using our damage model.
- Our damage model will play key role in operation planning as well as strategic decision making for loop efficiency and cost effectiveness.

Acknowledgements

- I would like to acknowledge my many wonderful colleagues for their contribution and support to this work:
  - Damage Rules Group
  - OSL Experimental Team
  - Management Support & Oversight

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