SHOT RATE IMPROVEMENT STRIVE FOR THE NATIONAL IGNITION FACILITY (NIF)

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Abstract

The National Ignition Facility (NIF) is the world's largest and most energetic laser experimental facility with 192 beams capable of delivering 1.8 megajoules of 500-terawatt ultraviolet laser energy. The energy, temperatures and pressures capable of being generated allow scientists the ability to generate conditions similar to the center of the sun and explore physics of planetary interiors, supernovae, black holes and thermonuclear burn. NIF has transitioned to a 24x7 operational facility and in the past year significant focus has been placed on increasing the volume of experimental shots capable of being conducted so as to satisfy the demand from the wide range of user groups. The goal for the current fiscal year is a shot rate of 300 (> 50% increase over the previous year), increasing to a sustainable rate of 400 the year after. The primary focus areas to achieve these increases are; making more shot time available, improvements in experiment scheduling, and reducing the duration of a shot cycle. This talk will discuss the control system improvements implemented and planned to reduce the shot cycle duration and the systematic approaches taken to identify and prioritize them.

INTRODUCTION

The National Ignition Facility (NIF) laser system [1] provides a scientific center for the study of inertial confinement fusion (ICF) and matter at extreme energy densities and pressures [2]. Each NIF experiment, or shot cycle, is managed by the Integrated Computer Control System (ICCS) [3], which uses a scalable software architecture running code on more than 2000 front end processors, embedded controllers and supervisory servers. The NIF control system operates laser and industrial controls hardware containing 66,000 control points to ensure that all of NIF's laser beams arrive at the target within 30 picoseconds of each other and are aligned to a pointing accuracy of less than 50 microns. Every NIF shot cycle [4] consists of approximately 1.6 million sequenced control point operations, such as beampath alignment, configuring diagnostics and arming triggers.

NIF has transitioned to a 24x7 operational facility and in the past year significant focus has been placed on increasing the volume of experimental shots capable of being conducted so as to satisfy the demand from its wide range of scientific user groups and maximizing the return of experimental data. The goal for the FY15 fiscal year was defined as a shot rate of 300 (> 50% increase over the previous year), increasing to a sustainable rate of 400 the year after. Figure 1 depicts the historical shot rate achieved on NIF and the goals going forward. Also indicated are the planned methods for achieving these goals:

- Formalizing a 24/5 shot week and increasing the number of weeks per year performing experiments (increased to 44 weeks)
- Improving the NIF shot scheduling paradigm by grouping similar shots to minimize the frequency of mid-week diagnostic reconfigurations
- Reducing the shot to shot durations. This includes both the shot cycle duration and the activities performed between each shot

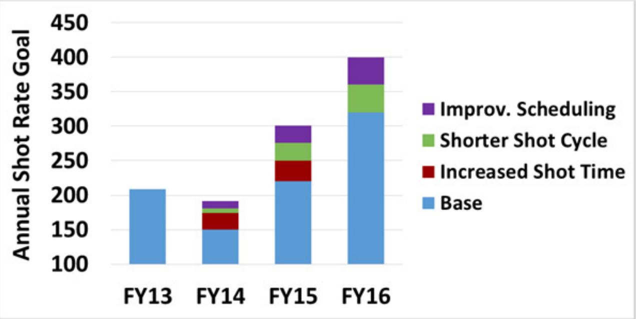

Figure 1: Historical and Planned NIF shot rates.

With both the increase in shot weeks and shot scheduling improvements commenced focus shifted to reducing the shot to shot durations. This work discusses the approach that was taken, a summary of the enhancements implemented and the results achieved.

ANALYSIS APPROACH

During each shot metrics are collected and archived that capture execution times of all phases and steps of the cycle. The mining of information from this vast data set was a critical component of the analysis and led to many of the identified improvements. To assist in rapidly visualizing these metrics the team leveraged the use of Splunk [5], a tool that we previously had extensively used

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to monitoring the health of the control system [6]. Splunk quickly highlighted key metrics at a high level for each shot cycle by presenting the data using a Gantt-like view with detailed information associated with each phase.

NIF shot cycle durations vary considerably depending of the complexity of the experiment and thus the metrics were subcategorized as such. The most recent 3 months of metrics were analyzed and a baseline defined to measure future success. Table 1 highlights these baseline metrics

Table 1: Q4FY14 Average Shot Cycle Durations

Shot Cycle Category	Average Shot Cycle Duration (Hours)
Warm Simple	19.6
Warm Complex	22.7
Cold	24.0
Layered	45.2

A top-down analysis was performed to identify the major shot activity sequences and determine, given system requirements and constraints, whether any resequencing could be performed to reduce the overall critical path through improved parallelization. In doing so both the critical path and 'close-to' critical path sequences were analyzed to ensure the evaluation of savings was accurate.

A bottom-up analysis was then performed on significant critical path activities to identify whether any could be optimized. As with the top-down analysis, Splunk greatly assisted in providing a rapid and consistent method to mine, visualize and identify the key significant activities worthy of further detailed analysis.

Return on investments were calculated on each proposed enhancement to ensure sufficient savings were achievable and that each was assigned the appropriate prioritization. The following section summarizes the major control system enhancements selected and implemented.

ENHANCEMENTS SUMMARY

Laser Preparation Parallel Shot Cycles

Top-down analysis identified that although laser energetic qualification was performed once target and diagnostic alignment were completed it could in fact be performed in parallel. There was no system requirement for this constraint other that the presently imposed automated shot cycle sequencing. A shot cycle enhancement was planned and implemented to allow NIF operations to perform these functions concurrently in two parallel shot cycles and synchronize once complete. This allowed the laser setup activity to be performed off-critical-path which resulted in reducing the overall shot cycle by up to 1 hour. Figure 2 presents a simplified Gantt view of the major shot cycle activities and depicts how they are now executed across two parallel shot cycles

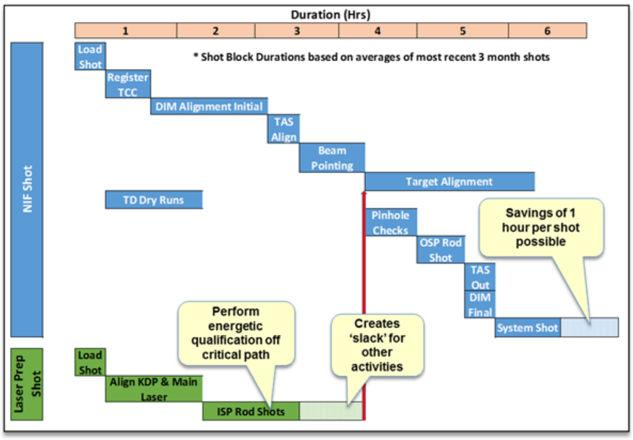


Figure 2: Parallel Shot Cycles Gantt View**.**

With the introduction of parallel laser preparation shot cycles two activities were identified to utilize the 'slack' time created. The first was the verification of amplitude modulation levels that is required following a facility wavelength reconfiguration (occurred 120 times during FY14). The second is the pulse shape calibration loop (Loop1) performed for high precision experiments (occurred 150 times during FY14). Both of these activities previously required discrete shot cycles to complete (2-3 hrs each).

Leveraging the new laser preparation shot framework, software modifications were implemented to optionally execute both these high frequency activities as part of the primary experiment and obviate the need for discrete shot cycles.

Target Alignment Assistance Tool

Target alignment sequences are typically one of the longest duration critical path activities and additionally had the greatest variances. Unlike NIF laser alignment, the target alignment process remains a largely manual process with some operator assists. The variations in NIF target types and alignment fiducials have historically made automating this process difficult. Much of the variance was identified to be caused by user input errors and experience levels in operational staff.

To aid with solving this, a new Target Alignment Assistance Tool (TAAT) was implemented. The tool uses Excel based script templates to semi-automate the manual alignment approach. The tool interfaces directly into the control system for measurement data provides the ability to embed alignment formulae, defined by subject matter experts, thereby removing opportunities for user input error. This data driven approach provides flexibility to adapt to novel target types and new alignment templates can rapidly be deployed without the need for any software modifications. Table 2 below details the reductions in user input achieved through use of the tool. In addition to a reduction of alignment time variance the use of the TAAT tool is saving approximately 30 minutes per alignment sequence over the previous manual approach.

Table 2: Comparison of User Input Savings Using TAAT

	# Measurements	# Moves	# Data Entries	# Move Choices
With Manual Alignment	1413	130	83	26
With TAAT	763	34	0	0
Savings (%)	46%	74%	100%	100%

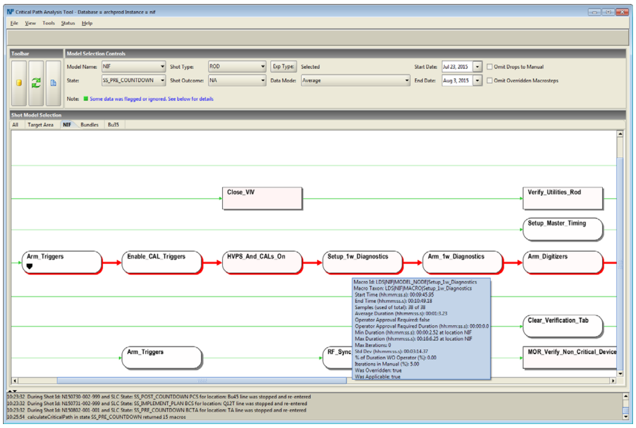
New Positioner Rules Of Engagement

Another source of alignment duration variance was found to be operator availability and coordination. Until recently the majority of the positioner movement rules of engagement required 2 operators (move requestor and move approver/observer). Lack of availability of one of the two required operators, due to various disruptions and distractions, often impacted the positioner alignment durations. To reduce the impact the rules of engagement were revised. The new rules resulted in the ability for a single operator to perform 90% of the shot cycle positioner moves without a secondary approver/observer whilst still ensuring machine safety was not compromised. The control software enhancements provide verification that the new rules are enforced. Only the final fine alignment steps, when positioners are within very close proximity, now require a 2 operator rule. The revised rules allow single operator positioner movements under the following circumstances:

- Concurrent positioner movements (insertions and retractions) for positioners outside the safe handoff boundary (1.4m from chamber center)
- Single positioner moves when no other positioners are unlocked and no other positioners are inside the critical zone (50cm from chamber center)
- Concurrent positioner retractions (z-only moves inside safe handoff zone) if none are deemed to be entangleable

Critical Path Analysis Tool

There was a significant initial effort required in manual data analysis to identify the critical path for a single or group of shot. It was challenging to identify how much slack existed in a non-critical path segment so as to accurately evaluate expected benefits from reducing the critical path. As we fully expected to continue to optimize the sequencing of the shot cycle we invested in the development of a Critical Path Analysis Tool (CPAT) to ease the burden of this analysis and to aid in measuring benefits from enhancements and to identify further gains. The tool provides far more detailed metrics than the manual analysis. Figure 3 displays a screenshot of the CPAT tool showing the visualization of a critical path segment of the shot cycle. The tool has already been used to identify sub-optimal sequencing of the pre-amplifier (rod) shot activities. With resequencing, 5 minutes have been saved of each of the 1300 rod shots fired annually which equates to approximately 11 additional shot cycles.



Critical Path Analysis Tool - Database = archprod Instance = nif

Model Name: NIF
State: SS_PRE_COUNTDOWN
Shot Type: ROD
Shot Outcome: NA
Exp Type: Selected
Data Mode: Average
Start Date: Jul 23, 2015
End Date: Aug 3, 2015
☐ Omit Drops to Manual
☐ Omit Overridden Macrosteps
Note: Some data was flagged or ignored. See below for details

Macro Id: LDS|NIF|MODEL_NODE|Setup_1w_Diagnostics
Macro Taxon: LDS|NIF|MACRO|Setup_1w_Diagnostics
Start Time (hh:mm:ss.s): 00:09:45.95
End Time (hh:mm:ss.s): 00:10:49.18
Samples (used of total): 38 of 38
Average Duration (hh:mm:ss.s): 00:01:3.23
Operator Approval Required: false
Operator Approval Required Duration (hh:mm:ss.s): 00:00:0.0
Min Duration (hh:mm:ss.s): 00:00:2.52 at location NIF
Max Duration (hh:mm:ss.s): 00:16:6.25 at location NIF
Max Iterations: 0
Std Dev (hh:mm:ss.s): 00:03:14.37
% of Duration WO Operator (%): 0.00
Iterations in Manual (%): 5.00
Was Overridden: true
Was Applicable: true

```
10:23:32  During Shot Id: N150730-002-999 and SLC State: SS_POST_COUNTDOWN PCS for location: Bu45 line was stopped and re-entered
10:23:32  During Shot Id: N150731-002-999 and SLC State: SS_IMPLEMENT_PLAN BCS for location: Q12T line was stopped and re-entered
10:23:32  During Shot Id: N150802-001-001 and SLC State: SS_PRE_COUNTDOWN BCTA for location: TA line was stopped and re-entered
10:25:54  calculateCriticalPath in state SS_PRE_COUNTDOWN returned 15 macros
```

Figure 3: Critical Path Analysis Tool (CPAT) example.

Final Optics Damage Inspection Optimization

A long critical path activity that occurs between shot cycles is the inspection of the NIF final optics. The activity uses a single camera located at target chamber center and it is positioned to inspect each optic set using a hexapod manipulator. With only a single camera, that needs to inspect up to 192 beamlines, the process can take over 3 hours to complete. By analyzing source code debug logging during a scan it was identified that by disabling focus motor braking during the scan of a single beamline and performing moves in parallel with reconfiguration of the backlighting laser that significant savings were feasible. The software modifications yielded savings of 50 minutes per scan. With inspections required 2-4 times per week the savings totalled 110 operational hours per year.

Diagnostic Foreline Vacuum Automation

Diagnostic reconfigurations between each shot can be a costly activity to vent and pump down following the exchange. To reduce the impact, vacuum automation was developed for the valve and hi-vac pump management system drastically reducing the amount of human interaction from industrial controls operations staff. Automation was added for 3 diagnostic positioners, the Cryo Target Positioner and 5 of the fixed diagnostic packages. The automation allows operations staff to initiate vent and pump cycles with a few button clicks and the automation manages the valve and pump control. The automation has significantly reduced operator interactions thus avoiding availability delays and potential for human error. Savings obtained range from 15-30 minutes per diagnostic positioner/package.

SHOT RATE IMPROVEMENT STATUS

With the majority of the shot rate improvements having now been deployed benefits obtained from them were measured. NIF set itself a challenging goal of 300 target shots during FY15 which represented a shot rate greater than 50% more than FY14. Figure 4 details the monthly shot volume and the average weekly shot rates achieved this year. As shown, NIF completed its goal 1 month ahead of schedule with an anticipated total annual shot count of approximately 350.

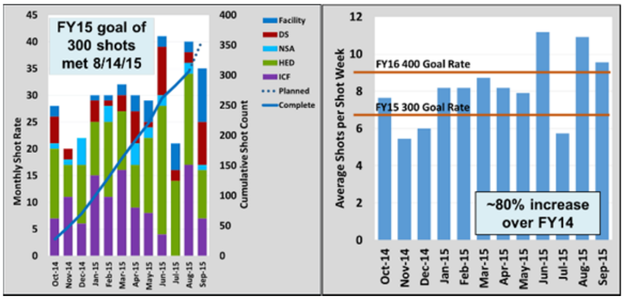


Figure 4: FY15 Shot rate metrics.

The two weekly shot rate threshold lines show the required rates for 300 and 400 annual shots respectively. During the final months of the year NIF exceeded the 400 shot rate threshold, with the exception of July due to a facility maintenance period, therefore we believe we are in an excellent position to meet the FY16 goal.

As a result of all the shot rate improvement initiatives, significant reductions have also been achieved in the shot to shot durations for all experiment categories as indicated in the table 3.

Table 3: Shot to Shot Average Duration Improvements

	Baseline Average Shot Cycle Duration (Hours)	Post-Optimizations Average Shot Cycle Duration (Hours)
Warm Simple	19.6	9.9
Warm Complex	22.7	11.7
Cold	24.0	12.3
Layered	45.2	23.0

FUTURE WORK

Although the majority of the shot rate improvement activities were completed in the past year NIF will be deploying three further major capabilities in the next two years to further benefit the shot rate.

'Gatling' shot cycle support to facilitate back to back system shots with only a single costly laser setup. Target exchanges are performed between each system shot and each uses a subset of the NIF beamlines. The first experiments are planned to be conducted this fall on NIF with a total of 8 shots expected to be performed in a 24 hour period which will represent a 3 hour saving for each additional shot performed in the series.

The Advanced Tracking Laser Alignment System (ATLAS) will use a laser tracking package for diagnostic positioner alignments and replace the existing alignment method using opposed port imaging systems. This method decouples the diagnostic alignment from the need to use the Target Alignment System (TAS) and thus removing the activity from the critical path.

Two additional Target and Diagnostic Manipulators (TANDM) are also being deployed over the next two years. These multifunction positioners will allow continuous layering on the Cryo target positioner without impacting the shot schedule. The TANDM positioners require the ATLAS system as no opposing port alignment system (OPAS) is being implemented for alignment.

CONCLUSION

This paper presents the systems based approach taken to identify and implement the major enhancements to increase the NIF shot rate in FY15 and the results achieved. Historical metrics proved invaluable in the process to accurately assess the cost of shot activities and rapidly isolate where improvements would yield the biggest gains.

Both a top-down and bottom-up approach to analysis produced results but the former (i.e. big picture) typically yielded the biggest returns. Capturing accurate return on investments was very important as it aided in selling the need for change and to assign the appropriate prioritization.

System reliability is also very important to analyze in a highly parallelized control system as a single underperforming component can be very costly in a system with overall speed governed by the slowest cog.

System optimizations are often best left until system is complete however it is very important to consider throughout the system design phases to ensure constraints are not being unnecessarily imposed that would limit optimization potentials in the future.

ACKNOWLEDGEMENT

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