THE ROLE OF DATA DRIVEN MODELS IN OPTIMIZING THE OPERATION OF THE NATIONAL IGNITION FACILITY

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Abstract

To meet the laser performance goals at Lawrence Livermore National Laboratory's National Ignition Facility (NIF), the NIF relies upon the Laser Performance Operations Model (LPOM) to automate the setup of the laser by simulating the laser energetics of the as-configured system. The physics engine of this model is a Java based simulation code called the Virtual Beam Line (VBL)[1]. VBL simulates paraxial beam propagation, amplification, aberration, spatial shaping and nonlinear self-focusing. Each of the NIF's 192 beam lines are modelled in parallel on the LPOM Linux compute cluster during shot setup and validation. On September 27th, 2013, with a 1.8MJ shot, NIF achieved the highest DT neutron yield to date, estimated at over 5×10^{15} (five quadrillion!). LPOM and VBL were key to delivering the required pulse shape and energetics.

THE NATIONAL IGNITION FACILITY

The National Ignition Facility (NIF) is a highly complex and energetic laser system. The primary objective for building the NIF is to achieve thermonuclear ignition and burn in a laboratory setting and to facilitate the task of stockpile stewardship [2]. The secondary efforts are to increase our understanding of materials science in general, and fusion as a potential carbon neutral renewable energy source.

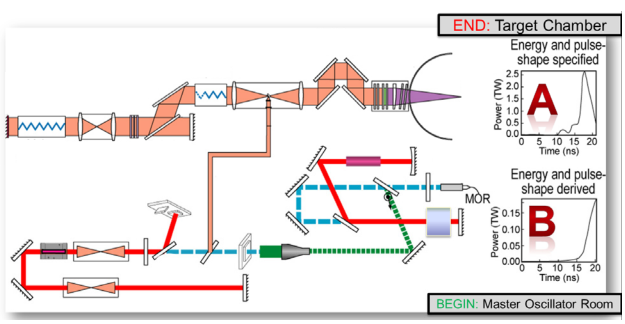

Figure 1: A sample beam line layout with Master Oscillator Room (MOR) at the beginning (B) and Target Chamber at the end (A).

The general goal of laser performance is to deliver the requested pulse shape at the target chamber center, to the ignition capsule, for all 192 beams at the specified wavelength. There are strict requirements on the temporal shape of the pulse, which are derived from the designed plasma-laser interaction for each experiment, see Figure 1 part A [3]. There is also a general requirement that the laser beam be flat in space. Spatial flatness is a critical laser performance requirement to ensure consistent illumination on all optics in the optical chain. If the spatial distribution of the beam has too much tilt or inhomogeneity it can lead to catastrophic intensifications and cause equipment protection failures.

It is the goal of laser performance to deliver the requested pulse shape (see Figure 1, A), and to do so we must accurately compute the input pulse shape with which to seed the laser (See Figure1, B). This process requires a series of iterative self-consistent VBL calculations, we call pulse solving, until a convergence criteria is met and equipment protection requirements are not violated.

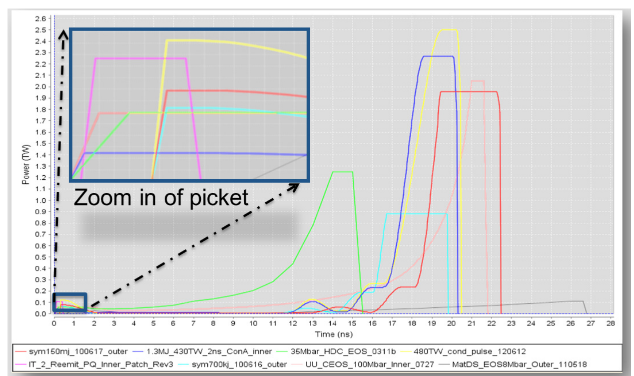

Figure 2: Example of pulse shapes for different experiments. Both small features (picket) and larger scale features must be accurately shaped.

SUPPORTING A VARIETY OF MISSIONS

Since the National Ignition Campaign (NIC) ended in 2012, we have seen an increase in the diversity of laser experiments conducted on the NIF laser. Each of these experiments typically require custom pulse shaping and precision control of the timing of all 192 beam lines. To truly capture the nonlinear effects and wide parameter space of the pulse shaping – you need a physics simulation code capable of modeling the behavior of the laser beam as it moves in time and space through each of the optics.

Figure 2 illustrates a grouping of various pulse shapes which have been shot on the NIF. The features important to precision shape include the timing of the main energy

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part of the pulse (i.e., the ‘peak’) after the beginning of the pulse, as well as a small feature we call the picket length (generally < 2 ns). In order to deliver quality pulse shapes, it is critical to meet shape requirements for all regions of the pulse. There is generally a tighter requirement on the peak, than the ‘trough’ (between the peak and picket), for example. The variety of pulse shapes seen in Figure 2 are indicative of variations routinely seen between subsequent shots on NIF. To increase the probability of success for a given shot, we employ both static and dynamic calibration adjustments, examples of which are given in the next sections.

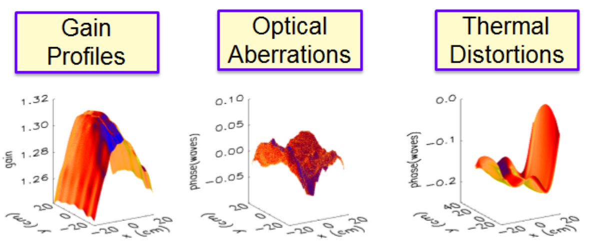

Figure 3: Sample of various spatial distributions which affect the beam’s performance as it interacts in the optical chain.

CAPTURING STATIC LASER CHARACTERISTICS IN THE MODEL

Each component of the laser chain, with which the beam interacts, has the potential to change the behavior of the beam in both intended and unintended ways. One example is that the amplification process is dependent upon where in space the beam samples a given amplifier. Thus to model it accurately we have to input a description of an amplifier slab’s starting gain distribution, and then track the beam’s interaction in space and time with each amplifying slab in the chain, see Figure 3. Over subsequent passes the amplifier does not get uniformly sampled, and thus has more gain available in some spatial regions than the others. To compensate, and amplify the beam uniformly, we adjust the initial spatial shape of the beam, see Figure 4.

Another example is optical aberrations, resulting of the imperfections of optical components, e.g., a lens or a mirror. Each component introduces some slight unintended disturbance in the beam (usually phase not amplitude). Generally we have commissioned each optic in the beam line to a specified tolerance (usually measured in waves of phase). We take these static measurements and use them as approximations for each optical component’s contribution to the phase aberrations for each beam line.

Because the various laser components (lens, slab, mirror, etc.) are finite and generally have a tilt and aberration associated with them, we must shape the beam upstream from the target chamber to account for all of these differences, so that by the time we enter the target chamber we get as spatially flat a beam as possible. Figure 4 shows a simplified chain illustrating the differences we see in beam shapes at various points. There are three locations on the beam path where the beam can be physically measured: at the Input Sensor Package (ISP), at the Output Sensor Package (OSP) and at the Target Chamber Center (TCC). Grossly simplified, to get a flat beam at TCC we shape the beam with a slight hump at the OSP. To get this slightly humped beam at the OSP we must shape the beam upstream at the ISP to have an asymmetric U shape. This complicates the modeling of the beam, and is a clear reason why care must be taken to predict the spatial profile of the beam in a given section of the chain.

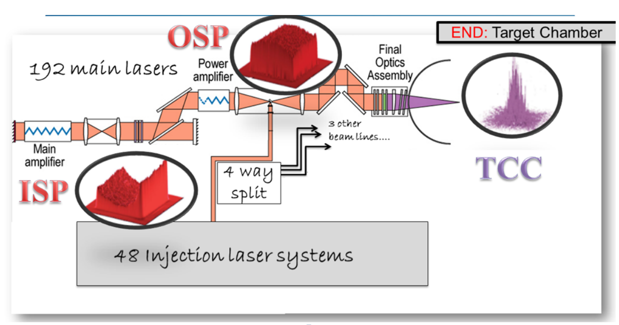

Figure 4: Simplified view of the main laser model showing the beam shape at the Integrated Sensor Package (ISP) the Output Sensor Package (OSP) and the Target Chamber Center (TCC).

CAPTURING DYNAMIC LASER PERFORMANCE IN THE MODEL

At shot cycle time (usually a 12 hour shift), in order to account for real time dynamic behavior in the beam path atmosphere and other effects not present in our model, we take a series of shots we call ‘Rod Shots’. Rod shots mimic the final system shot of the experiment, except they do not flow through the final main laser portion nor undergo amplification outside of the injection system. The beams are taken from the ISP and run to the target chamber TCC without turning on any flash lamps in the Main Amplifier (MA) or Power Amplifier (PA). This is a critical piece to delivering accurate laser performance. An example of how this cycle is performed is given in Figure 5.

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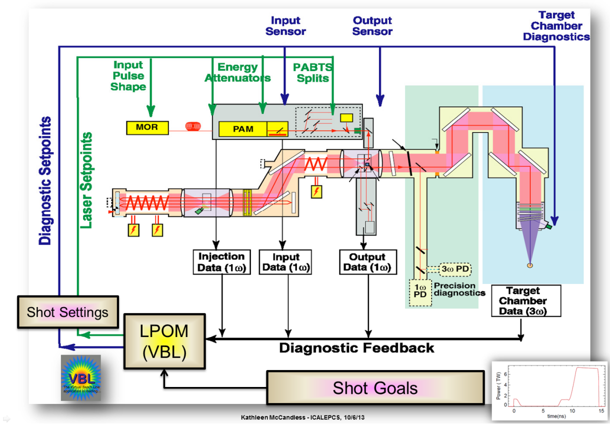

Figure 5: Diagram showing the cycle of data flowing into the laser setup from LPOM (Blue and Green) and back into the LPOM model (Black).

IDENTIFYING TRENDS TO IMPROVE PERFORMANCE

Unfortunately the performance of an optical component degrades over time. This quality is hard to assess – without dismantling and sending each component to a lab for forensic analysis – it is best suited to tracking the performance on a shot to shot basis to look for a general trend of degradation. An example of how we do this occurred last July 2013. We took a shot and saw for several beam lines (beam line BL211 in Figure 6) that the performance at TCC was significantly worse than the performance earlier at the exit of the main laser (OSP).

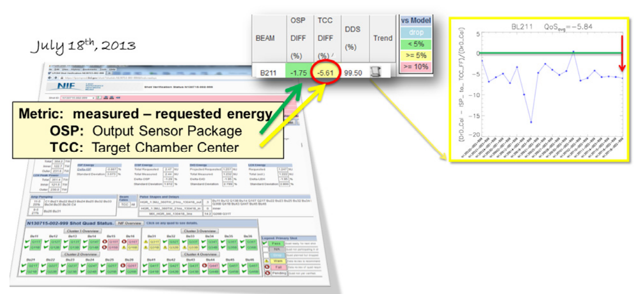

Figure 6: LPOM's web dashboard alerts laser physicists to potential problems on each quad and beam line.

By reviewing the trend over the past 20 or so shots, see Figure 6, we can see that on average there has been a deviation of about -5%. When we identify trends like these, we can elect to make adjustments to the model for a section of the laser chain (in this case the section after the OSP before the TCC) as a multiplier on the transmission we expect to achieve. Indeed such an adjustment was made on July 19th, we asked for 5% more power on beam line 211 in order to most accurately meet the request. As you can see in Figure 7 – we succeeded and delivered excellent performance at both the exit of the main laser and at the target chamber center – due to our diligence in spotting this trend and making the adjustment.

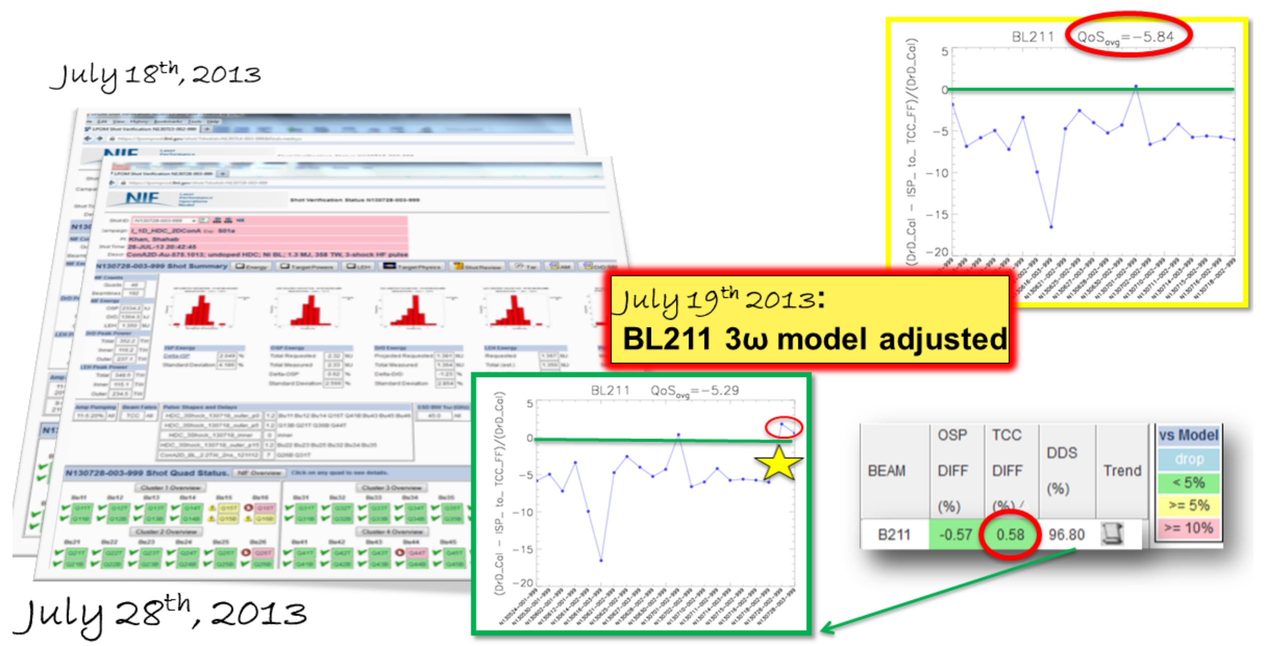

Figure 7: After adjusting the model on July 19th, we delivered excellent performance on the subsequent shots. July 28th is shown here to be within 0.5%, down from 5% previously.

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CONCLUSION

In order to achieve excellent laser performance we require the ability to assess and understand static laser component properties and performance, dynamic laser system behaviour (variations due to the actual weather and temperature), and to identify trends that occur over time – such as the beam line or quad specific degradation in performance. The ability to perform selective calibration of components to fine tune the performance characteristics are key to our continued success as a world class laser physics institution.

ACKNOWLEDGMENTS

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