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UCRL-CONF-234340

Laser Energetics and Propagation Modeling for the NIF

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September 6, 2007

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Kobe, Japan
September 7, 2007 through September 14, 2007

Disclaimer

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Abstract. Design, activation, and operation of modern high-energy, fusion-class lasers rely heavily on accurate simulation of laser performance. Setup, equipment protection, and data interpretation of the National Ignition Facility[1] (NIF) at Lawrence Livermore National Laboratory (LLNL) are being controlled by a Laser Performance Operations Model (LPOM)[2], which, at its core, utilizes a Virtual Beam Line (VBL) simulation code to predict laser energetics, wavefront, near- and far-field beam profiles, and damage risk prior to each shot. This same simulation tool is being used widely to understand such diverse phenomena as regenerative-amplifier saturation, damage inspection system performance, fratricide risk from small-scale flaws in large optics, converter performance, and conjugate image formation.

1. Object structure

The VBL code has been constructed in Java with strict attention paid to maintaining an object-oriented architecture. The two primary objects in the code are the part, a composite structure of interactions, and the beam, which visits the parts in either a pre-determined or discovered order. The function of each part is to interact with the beam, thereby modifying the beam and possibly itself.

The part contains a list of surfaces and possibly a material. It interacts with the beam by delegating to these objects where the specific physics models are implemented. Examples of interactions with surfaces are reflection, transmission with refraction, linear- or nonlinear absorption, and spawning of daughter (ghost) beams. The shape of the surface can alter the beam's wavefront curvature, leading to focus effects. The surfaces may also contain layers whose interactions consist of such effects as aberrations, masks, or dumping an image of the beam to disk for later processing. The material implements a series of split-steps consisting of interleaved vacuum propagation steps and near-field interactions. These latter include effects like saturated gain, bulk loss, nonlinear- and bi-refringent index effects, frequency conversion, and multi-wavelength cross phase modulation.

The beam is a visitor to the parts of the laser which tell it what to do as steps in the interactions. Although the beam structure is more general, the only form that has been implemented to date is the diffractive beam whose space-time structure is defined by a contained basis distribution. This inherits from a more general distribution object which associates one or more values (either real or complex) with any space-time point. In

the case of basis distributions, data is held on a rectangular grid of locations, and the distribution contains an interpolator that defines values between the grid points. A basis distribution may be of type Fourier or Hankel, instantiating the general 2D or circularly-symmetric beam models.

2. NIF Model

As indicated in Figures 1 and 2, VBL has become the simulation tool used for modeling NIF's optical behaviour and set-up and equipment protection during ongoing NIF commissioning activities and for the Precision Diagnostic System campaigns[1,3]. As part of this activity, we have developed input models that contain measured data for most aspects of the laser components.

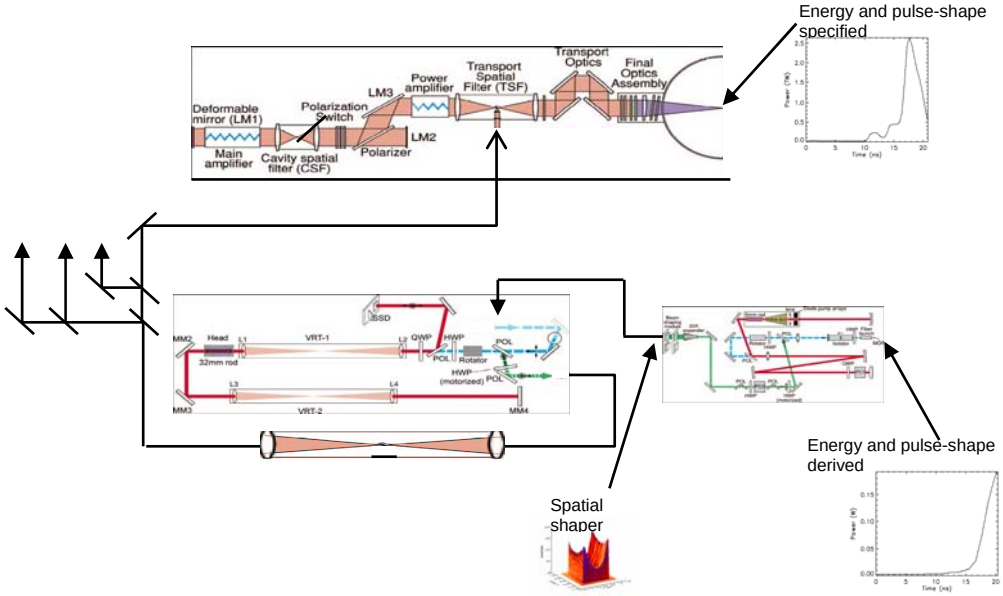

Figure 1. VBL is being used to model NIF performance from the 1 nJ beam at the fiber launch from the master oscillator all the way to the focused beam energy, power, and spatial shape at the target. Shot setup relies on VBL's pulse solver which derives the energy and temporal power variation at injection to the regenerative amplifier that will lead to the energy and pulse shape specified at the target.

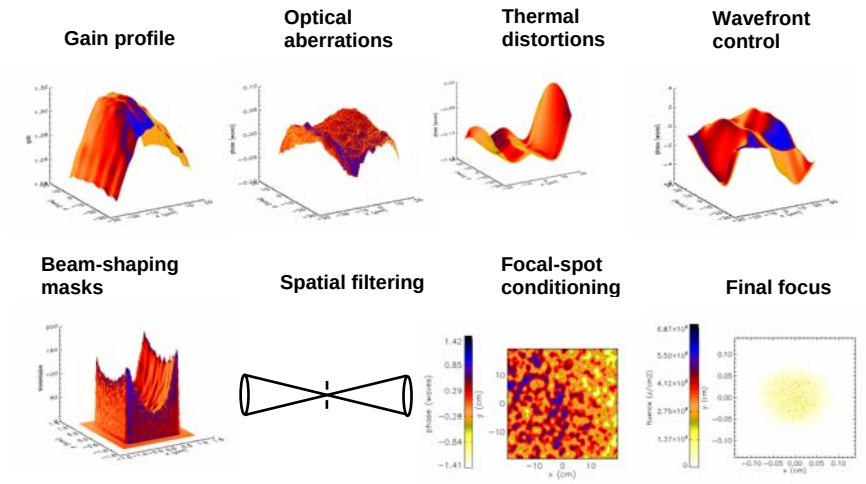

Figure 2. Modeling NIF performance is based on quantitative measurements of all aspects of the laser, including gain profiles and the shaping masks implemented to compensate for them, various sources of optical aberrations, and the deformable mirror that compensates for them, spatial filters and image relaying, and the various techniques being used to control the shape of the farfield spot.

3. Code Performance

The choice of Java as a development language was driven by the large variety of tools available to speed the development cycle as well as their integration among themselves and with internet protocols. Similarly, xml was selected for representing data structures because it is a universal standard with self-describing data that automatically separates the data model (xml) from its presentation (xslt). Strikingly, we have found that, because of improvements in on-the-fly byte-code optimization, there is little or no penalty in execution speed associated with these choices. Figure 3 compares execution times between VBL and its predecessor code, Prop, in modeling one of NIF's beamlines at varying computational grid resolutions. These comparisons were made on a 2.4 GHz Xeon dual processor, utilizing Intel's Fortran compiler and Math Kernel Library. As can be seen, VBL is somewhat faster than its predecessor, despite Prop's being written in highly-optimized procedural Fortran. This advantage comes principally from increased efficiency in the fast Fourier transforms, where the methods in VBL are the same as those in Prop.

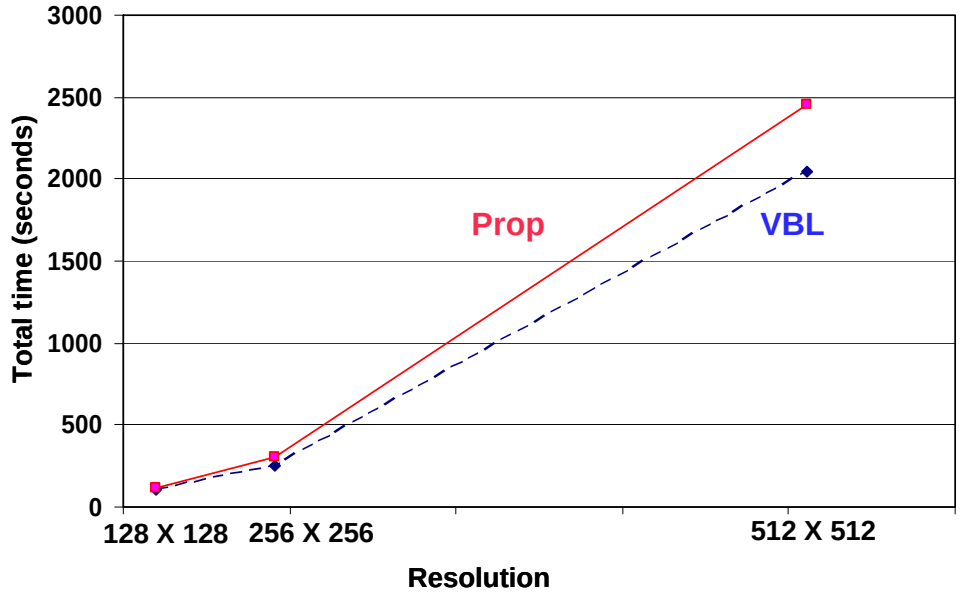

Figure 3. Timing comparison between VBL and its predecessor Fortran code, Prop. Despite the time penalty associated with object creation, VBL is slightly faster than the procedural Fortran code.

4. Pulse Solver

During NIF operations, the experimenter typically specifies the temporal power history of the pulse that is incident on the target. The ignition campaign, for example, requires a complex, high-contrast pulse shape which must be matched to within a few percent, and for which the RMS deviation among NIF's 192 beams must be reliably small (less than 3% on the peak). To accomplish this challenging task, NIF relies on VBL's ability to solve for the pulse shape at the injection into the regenerative amplifier which will yield the specified pulse shape at the target. This process is illustrated in Figure 1. The derived P(t) at the regen entrance is quite different from that specified at the target chamber, due principally to saturation in the gain media and irradiance-dependence of the frequency conversion process. When this pulse shape is run forward

through the laser model, the match to the desired pulse is better than 1%. This is sufficient to assure that residual errors in the pulse-shaping process are dominated by differences between the laser and the laser-model, not by the numerical solver routine.

By default, VBL treats gain saturation through a time- and position-dependent Franz-Nodvik model, which models both the temporal distortion of the pulse shape and the tendency of saturation to decrease beam contrast. Franz-Nodvik is an exact solution of the non-diffractive energy extraction equations in the limits of either zero or infinite lifetime of the lower level of the lasing transition (with different saturation fluences). In the intermediate regime, the temporal energy-extraction equations[4] must be solved numerically. To support applications where that level of precision is important, VBL has an option to include this effect. As seen in Figure 4, we find that the difference between τ=0 and τ=250 ps in the NIF laser glass can affect the predicted ignition pulse shape by as much as ~2% at the peak – a large fraction of the allowed error.

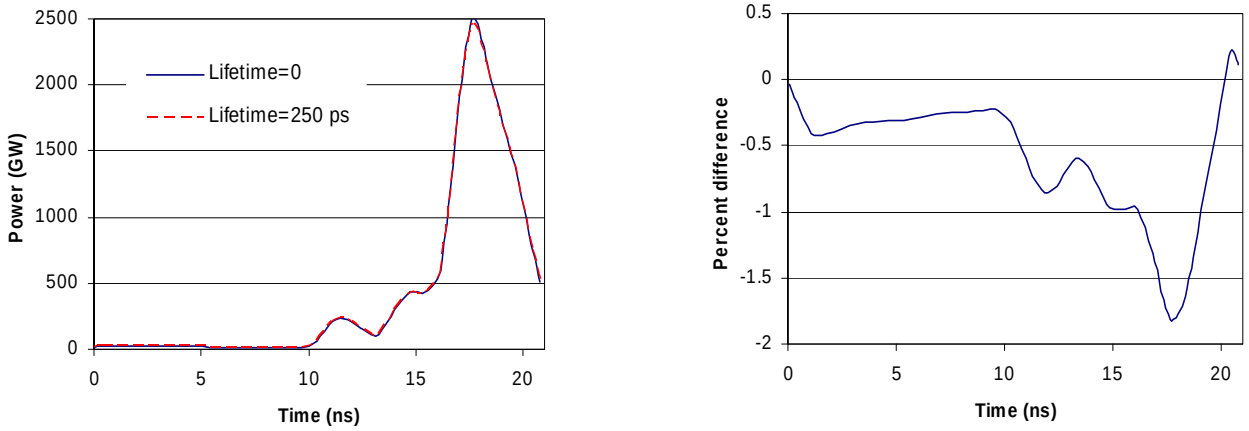

Figure 4. Numerically solving the extraction equations for a full-NIF simulation, we calculate about a 2% effect on peak power for an ignition pulse.

5. Frequency Conversion

VBL's ability to accurately model the conversion of the main laser pulse at wavelength 1.053 μm to its second or third harmonic, in the visible and near-UV respectively, is crucial to fulfilling its mission of enabling NIF to operate confidently and predictably at its design energy, power, and precision. Our model is based on the paraxial theory of Eimerl, Auerbach, and Milonni[5], with a modification to the nonlinear cross-phase modulation developed by Henesian (unpublished).

Over the past two years, while continuing its build-out and commissioning activities, the NIF program has carried out a series of detailed measurements on its Precision Diagnostics System, of the performance of a single beam of the laser. Included in these measurements, is the performance of a final optics assembly (FOA) which is a prototype of the production FOA to be deployed on the target chamber. Figure 5 illustrates the accuracy with which the VBL model is able to reproduce both the whole-beam energetics and the spatial structure of the conversion process.

6. Human interface

For backwards compatibility, VBL was required from its inception to be able to accept and parse the same input files used by the Prop code. This defined a user interface, and led us to devote most of our efforts to expanding and validating its physics feature set. As features were added that were beyond Prop's ken, we simply extended the original grammar to encompass them. Recently, we have begun to pay more serious

attention to developing an environment that is more user friendly, especially those who are not necessarily familiar with the language of the Prop input file.

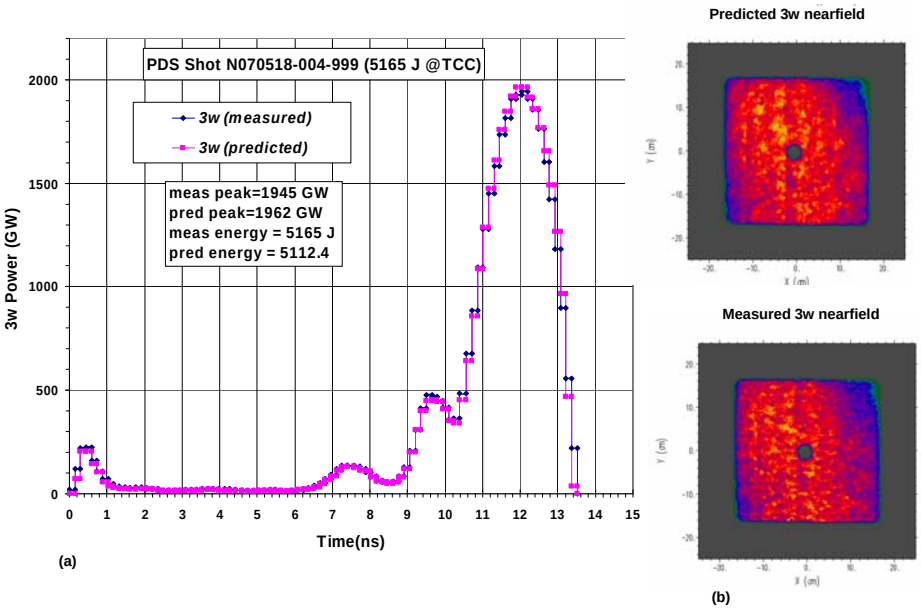

Figure 5. (a) Overlay of predicted and measured UV pulse shapes for a 1 MJ (full NIF equivalent) PDS shot taken on May 8, 2007. (b) Predicted and measured 3w nearfield fluence profiles. The prediction is made using 1ω nearfield, P(t), and phase measured in PDS at a plane nearly equivalent to the input to the doubler crystal.

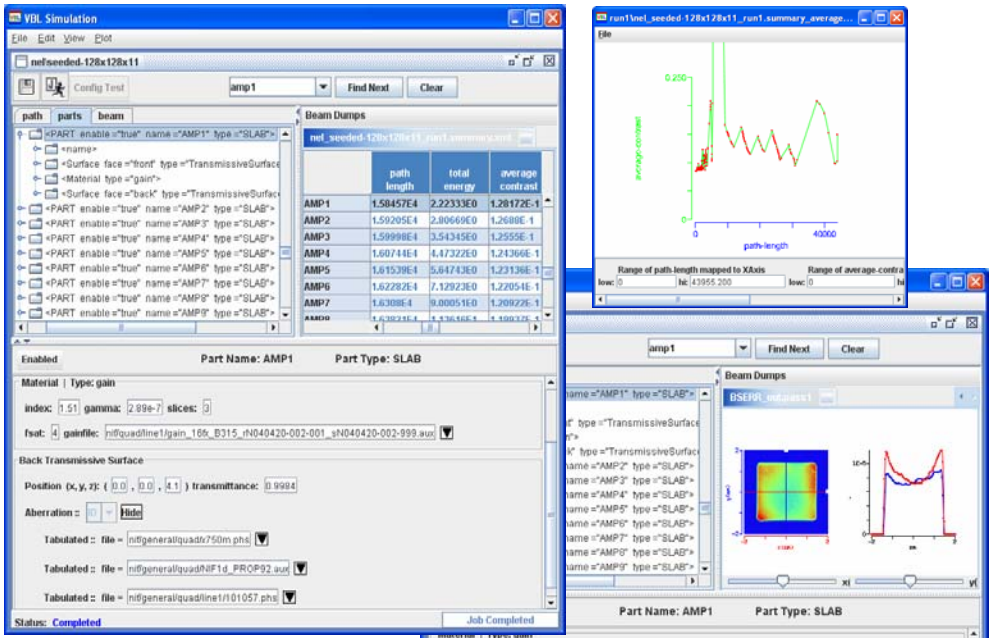

Figure 6. Screen shots from a GUI being developed for interfacing with VBL.

Figure 6 shows a set of screen shots from a graphical user interface (GUI) being developed for supporting parametric studies using VBL. The top left pane shows a fold-out view of the parts in a laser chain, in the order in which they are defined. This is a searchable list. Clicking on any part expands the bottom menu into an editable description of its properties. The running-man icon at the top left initiates a run with these newly-set properties. There are similar panes shown for viewing the beam properties and path. After the run, the results are viewable in tabular or graphical form. Plots of integrated properties vs. z, or of time-dependent properties vs. t at a given location, can be produced by simple right-clicks on this summary screen.

Beyond setting up and running jobs and viewing the results, we want VBL to assist us in maintaining a common model of the laser, tracing the history and bona fides of all input data, tracking the history of both the laser performance and the laser models, and sharing results to minimize duplicate efforts. To facilitate this, we are developing an Oracle-based referential database, tied to the GUI.

As one example of the value of this database, consider a user who wishes to recall a previous run, modify it in some way, run the modified case, and store the results back into the database for future use. Using the VBL GUI, he could specify the run through such features as title, date, the user who made the run, and/or key-words in descriptive notes associated with it. Transparently to the user, the GUI would query a "Run" table which would retrieve a complete description of the beamline and the injected beam from the associated tables. That description will appear on the GUI, where the user may display and plot results of the run, modify and re-run, compare the new results with the old, and create a new entry in the database.

7. Conclusion

The challenging performance requirements of the NIF laser require accurate, versatile, and easy-to-use laser simulation capability. VBL is an ongoing project to supply this capability. Adherence to an object-oriented paradigm, and use of available powerful development tools has allowed us to make rapid progress with limited manpower. While we continue to expand and refine our physics models, we are beginning to devote increasing attention to human interfaces that will make numerical studies of laser dynamics both easier and more reliable.

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Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.