Optical Time Domain Reflectometry for the OMEGA EP Laser

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Abstract

Optical Time-Domain Reflectometry (OTDR) refers to the return of light back through the laser after it is fired. The OTDR device at the laser source is used to track the return signals of that light. When a shot is fired, the laser beam passes through several optical components on its way to the target chamber. When passing through each optic, a small amount of the laser is reflected backwards through the laser. Anti-reflective coatings help reduce the reflection, but if they malfunction, a significant percentage of the laser's power can be lost. When the reflected signals arrive back at the laser source, they are recorded by the OTDR. A computer program has been written to handle the OTDR data on the new OMEGA Extended Performance laser. The program finds all the return signals and if there is an unexpected spike, it will identify which optic it came from. The program produces a user-friendly display of all reflected signals to allow easy interpretation and corrective action.

Introduction

The Research Project - Purpose and Rationale

The research topic involving computed optic failure identification using Optical Time-Domain Reflectometry (OTDR) was chosen because there was no existing method on the current or new laser to easily identify which of many optics had failed and needed to be replaced in order to maintain peak system transmission of light to the target. Knowing which optic has failed will minimize system down time needed to identify and replace failed optics and to maximize energy on target for each experiment using the laser(s). When system down time is minimized, the number of shots per unit time increases. This allows more experiments to be conducted. When energy to the target is insufficient, certain experiments cannot be conducted at all or will need to be repeated. In general, progress in support of the laboratory's mission is diminished if on-target energy is insufficient or if a reduction in the number of shots is encountered. The ability to quickly and correctly identify the specific optic that has failed is important to the success of the laboratory. The research project deliverable meets this need for the new laser and closes a gap in the capabilities of the existing laser.

The research project consists of two major components: Optics and Software.

OMEGA Extended Performance (EP)

The OMEGA EP laser will provide the Laser Laboratory with a new resource to explore research into laser-driven fusion in order to obtain a cheap and renewable source of energy. This new laser is built tangent to the existing OMEGA laser; the two lasers will work together to perform experiments neither could do alone. The new experiments possible with the OMEGA EP laser will advance science towards the ultimate goal of achieving fusion, most directly through experimental support of the National Ignition Facility under construction.

The OMEGA EP laser uses a new multi-pass architecture, which means that the light from a single laser shot is reflected so that it passes through the same optical components, in particular the amplifiers, multiple times. This is much more efficient than passing through different, identical optics, and results in a very powerful laser by the time it hits the target.

Figure 1.0 below shows the path of the laser beam from the source to the target.

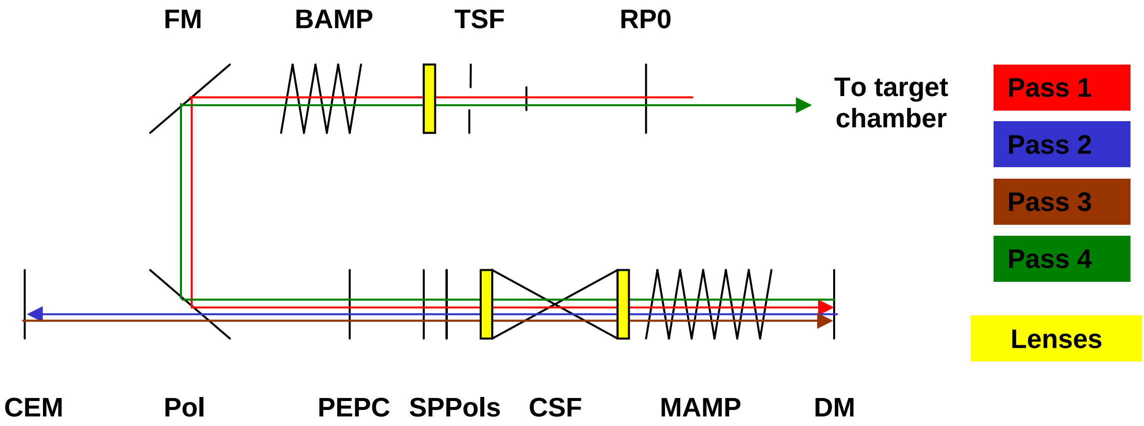


Figure 1.0 Omega EP laser light path

RP0 = Laser Source
TSF = Transport Spatial Filter
BAMP = Booster Amplifier
FM = Fold Mirror
MAMP = Main Amplifier

POL = Polarizer
PEPC = Pockel Cell
SPPOLS = More Polarizer
CSF = Cavity Spatial Filter
DM = Deformable Mirror

CEM = Cavity End Mirror

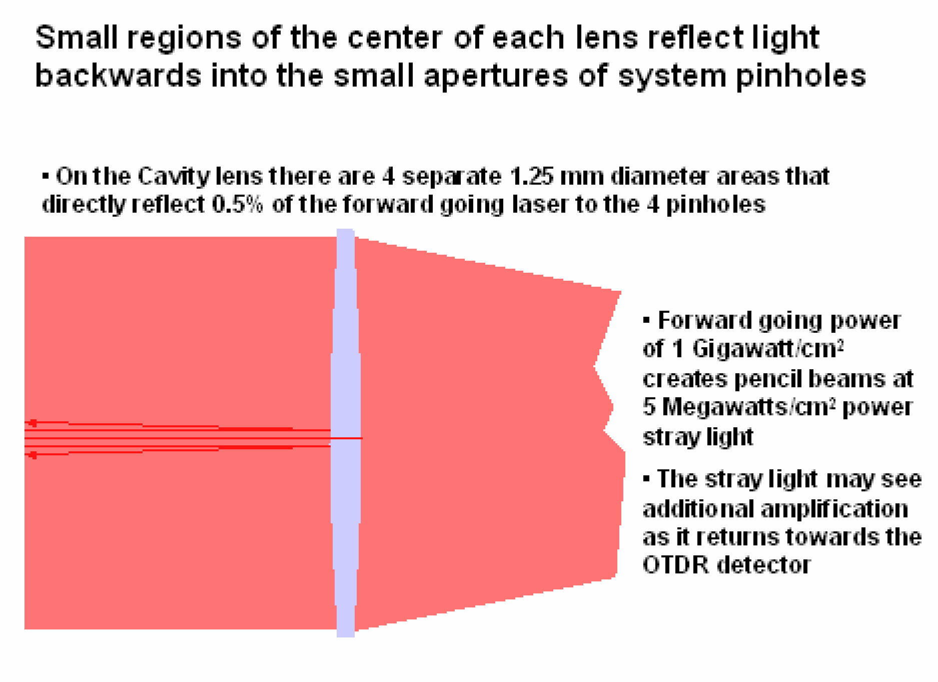
Optical Time Domain Reflectometry

When the laser beam passes through the optical components of the OMEGA EP laser, small amounts of light are reflected back through the laser towards the laser source. While the percentage of the beam normally lost per optic is small, by time the laser beam hits the target, the beam could have passed through enough optics that there could be insufficient energy left in the beam. If an optic is damaged or has failed, the on-target energy could be severely diminished.

Anti-reflection coatings can reduce the amount of reflected light to an acceptable amount of 0.05% per optic. However, during a shot, an immense amount of energy is fired through the laser, meaning that over time, some coatings may become damaged. When this happens, the light reflected by the damaged optic is greatly increased, resulting in the needless loss of energy. This situation could impact the success of the experiment and the ability of the Laser Lab to ultimately achieve its mission.

To keep track of the reflections back to the laser source, a detector and oscilloscope are installed at the point of laser beam initiation. The oscilloscope produces a signal of the light coming back through the laser (amplitude vs. time) that can be read to determine if all reflective coatings and optics are working properly. If an optic is malfunctioning, there will be a large unwanted spike in the graph, representing the increase in reflected light.

By noting the time that the spike occurred, a computer program can determine which optics are causing the high return signals and display them to the user. Once identified, the damaged optic can be replaced or repaired so that the beam no longer loses a critical amount of energy. Figure 2.0 below shows an example of how reflected light from a lens occurs.



Small regions of the center of each lens reflect light backwards into the small apertures of system pinholes

- On the Cavity lens there are 4 separate 1.25 mm diameter areas that directly reflect 0.5% of the forward going laser to the 4 pinholes

- Forward going power of 1 Gigawatt/cm² creates pencil beams at 5 Megawatts/cm² power stray light
- The stray light may see additional amplification as it returns towards the OTDR detector

Figure 2.0 Lens Based Reflected Light Opportunities

Method

Data Tables

Data containing the future spatial placement of the optical components of the EP laser were available at the beginning of the project. They were used to fill the database that the computer would use when calculating the sources of the return signals in the laser.

MATLAB

The program used for the creation of the Graphical User Interface and calculation of sources was written using MATLAB M-files and GUI editors. All code was written in the MATLAB language.

Optical Analysis

Optical Time Domain for Equal Path Scenarios

When the laser is fired, every optical component that is passed through along the way to the target has the potential to generate a return signal that would make it back to the laser source. Lenses have the greatest probability to create such signals. The most common way that light is reflected backwards through the laser is called an equal-path scenario. This means that the light will hit the optic, and its reflected inbound path to the detector (the path taken to get back to the laser source) will retrace its outbound path from the source (the path originally taken to reach the optic).

In order to predict when such possibilities may reach the oscilloscope, the time delay for the light to reach any given optic must be doubled; the resulting value accounts for the time taken to travel the inbound and outbound paths (which are equal) and thus accounts for the total path. This calculation was performed for each optic so as to create the time-based values for the return signal for every equal-path scenario.

OTD for Unequal Path Scenarios

While most cases for the return of laser light are equal path scenarios, there are specific cases where the paths of the outbound beam and the inbound beam are unequal. This occurs because of the multi-pass architecture of the EP beam path. Since the multi-pass system causes the laser beam to pass through the same optics multiple times, returning laser light could end up 'bouncing' around in the laser cavity. This creates scenarios where the inbound path is greater than the outbound path. Also, there are scenarios where the returning light's inbound path is less than the outbound path. For example, if the laser was on pass 3, passing towards the Deformable Mirror for the second time, but was reflected, it could follow a short path directly back to the laser source.

This bouncing creates possibilities for the laser beam to arrive at the laser source at unusual times. For example, if the laser bounces around the cavity and finally arrives back at the laser source at 1000 ns after the shot, but there is no optic at 500 ns delay, this then represents situation of unequal inbound and outbound path lengths. Figure 3.0 shows an example of an unequal path scenario.

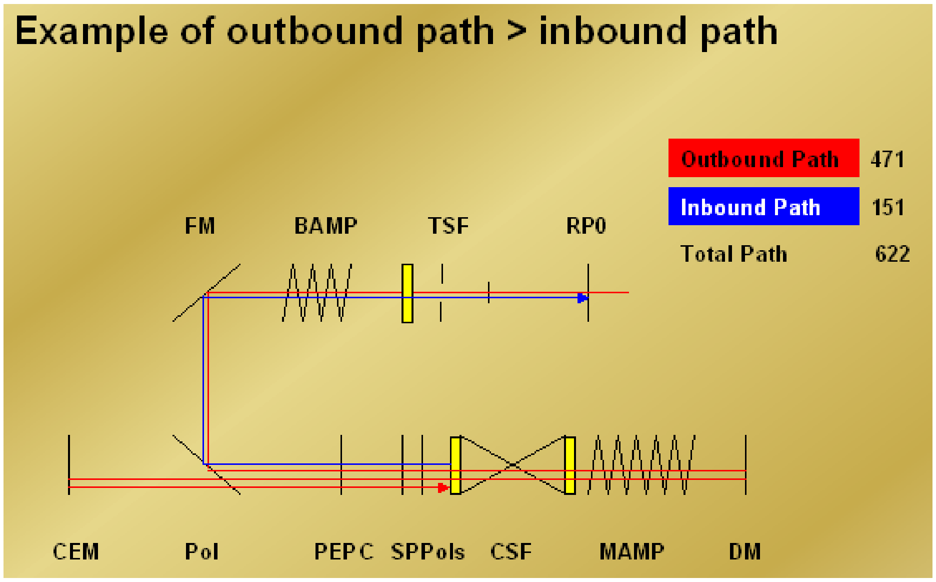


Figure 3.0 Unequal Path Scenario

The number of lenses that the laser beam passes through limits the number of unequal path possibilities. Because there are a total of ten passes through lenses, there are only ten cases where an unequal path scenario could occur. For each of these ten, the path the bouncing light would follow was traced, and the total time delay of the new path was then calculated. The results of these calculations were then added to the program's database, so that when unequal path scenarios occur, they do not confuse the program. Instead, it recognizes the arrival times of those ten cases as what they are. For example, if case 7 results in the laser beam returning at 1250 ns, and case 7 occurs, the program recognizes the 1250 ns to mean that case 7 has occurred.

Some of the unequal paths overlap in expected return times. This is because the inbound path of one scenario is often equal to the outbound path of another and vice versa, resulting in two possibilities. If this happens, the program will list both possibilities for investigation.

Finally, the reflections measured at the detector will only be those of primary reflections of equal and unequal path lengths. In other words, any signal from secondary or more reflections will simply be too small to measure and in any event, would be below the threshold of interest.

The finished database contains the data for all equal path scenarios, along with all ten unequal cases. Thus, the program has knowledge of every predictable scenario in which laser light may find its way back to the laser source. Using the data from the oscilloscope after a shot, the program will use the database to calculate where the return signals came from by comparing the time delay of the return signals to the list of return signal possibilities in the database. In the unlikely event that an unforeseen reflected return time is obtained, the program will list the return time and indicate a need for further investigation.

Software Development

Iterative Process

The approach to developing the software was a highly planned and iterative method. Before any code was written, the requirements were analyzed to determine what exactly the end program needed to do. Then, elements of the program were planned to specifically meet those requirements. After those elements were designed, they were compared to the original requirements to see whether the requirements were indeed being met. Only then was code written. After the code was complete, and at several steps along the way, it was again checked against the original requirements to make sure the program was going to do what it needed to do. This iterative process is known as the RUP, (Rational Unified Process) method of programming. It resulted in the end-product-program doing exactly what it was meant to do. Figure 4.0 shows a flow diagram of the Rational Unified Process.

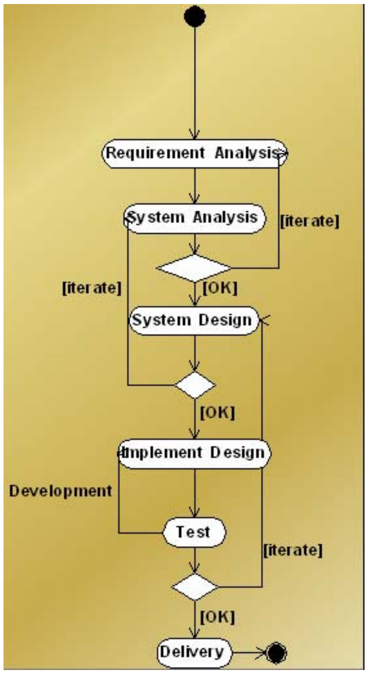


Figure 4.0 Rational Unified Process

Creation of OTD Databases

Data was inserted by rows into a database where information on each optical component is stored. Information such as component ID, component label, and time delay were kept for each component. When the program accesses the database it gains knowledge of the entire laser beam system because it contains all vital information on all components of the laser.

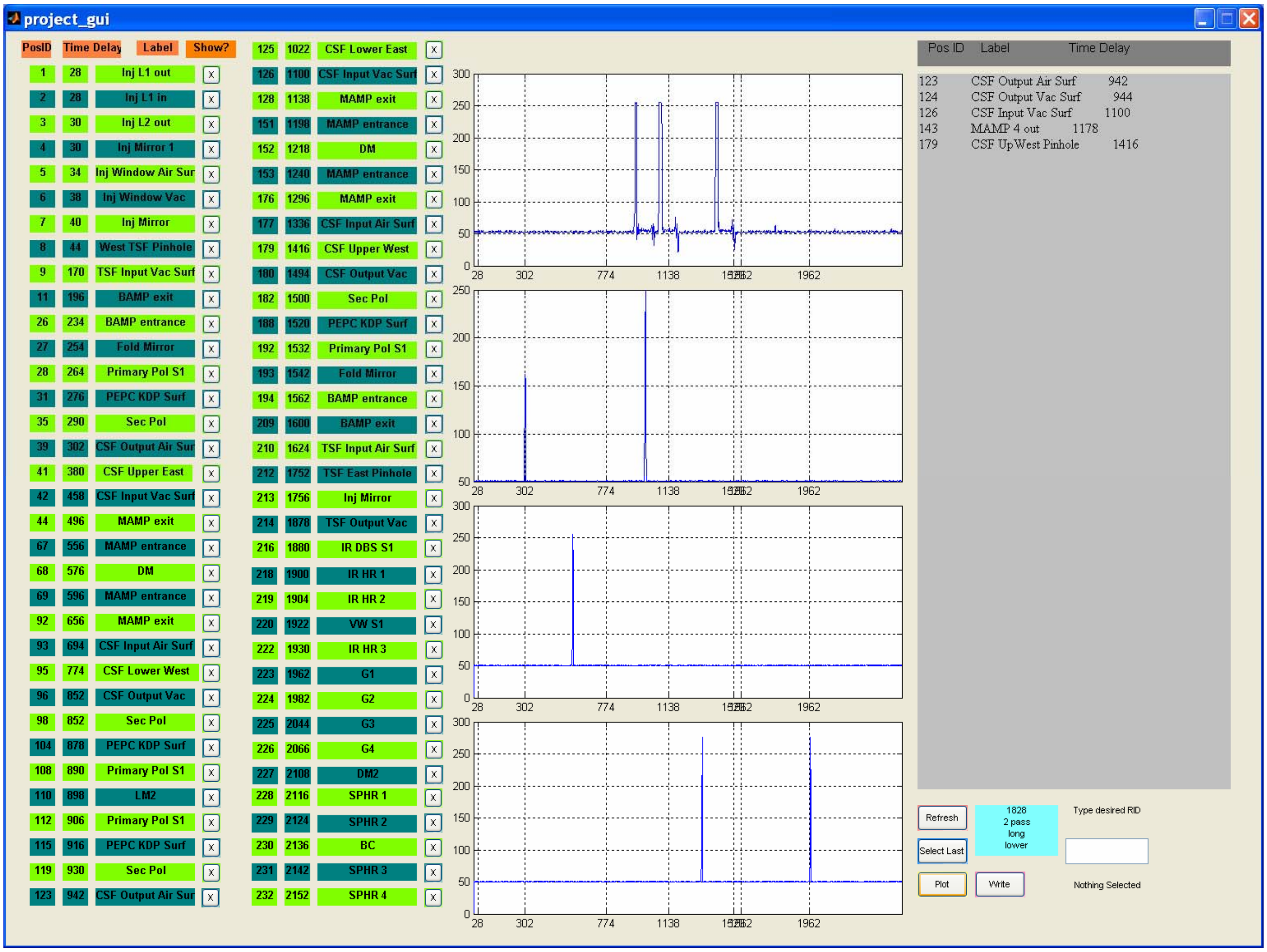
Internal Working of the Program

After each shot from the laser, the OTDR program will be launched. It will establish a connection to the database containing time delay data. For each return signal, it compares the time of the return to the times in the database and looks for matches. The matches are where the program calculates the return light to come from.

Output

The end output of the program is a graphical user interface that displays a graph of amplitude vs. time of return signals for each beamline (total of four graphs) and a table summarizing the signal spikes and their likely origin. Also, the GUI has several buttons that allow for commands, like saving all of the data for the past shot in an .hdf file for future reference, or loading the data for those past shots to be viewed again.

The program allows for user customization of the display. Each optical component has a corresponding “tick mark” on the graphs. The tick marks can be toggled on or off by the user. The tick mark toggle changes the appearance of the graph in such a way as to visually align the tick mark with the spikes to more readily discern which components are the causes of the return signals. Figure 5.0 below shows the output of the program that facilitates user understanding and interpretation of the results.



PosID	Time Delay	Label	Show?
1	28	Inj L1 out	X
2	28	Inj L1 in	X
3	30	Inj L2 out	X
4	30	Inj Mirror 1	X
5	34	Inj Window Air Sur	X
6	38	Inj Window Vac	X
7	40	Inj Mirror	X
8	44	West TSF Pinhole	X
9	170	TSF Input Vac Surf	X
11	196	BAMP exit	X
26	234	BAMP entrance	X
27	254	Fold Mirror	X
28	264	Primary Pol S1	X
31	276	PEPC KDP Surf	X
35	290	Sec Pol	X
39	302	CSF Output Air Sur	X
41	380	CSF Upper East	X
42	458	CSF Input Vac Surf	X
44	496	MAMP exit	X
67	556	MAMP entrance	X
68	576	DM	X
69	596	MAMP entrance	X
92	656	MAMP exit	X
93	694	CSF Input Air Surf	X
95	774	CSF Lower West	X
96	852	CSF Output Vac	X
98	852	Sec Pol	X
104	878	PEPC KDP Surf	X
108	890	Primary Pol S1	X
110	898	LM2	X
112	906	Primary Pol S1	X
115	916	PEPC KDP Surf	X
119	930	Sec Pol	X
123	942	CSF Output Air Sur	X
125	1022	CSF Lower East	X
126	1100	CSF Input Vac Surf	X
128	1138	MAMP exit	X
151	1198	MAMP entrance	X
152	1218	DM	X
153	1240	MAMP entrance	X
176	1296	MAMP exit	X
177	1336	CSF Input Air Surf	X
179	1416	CSF Upper West	X
180	1494	CSF Output Vac	X
182	1500	Sec Pol	X
188	1520	PEPC KDP Surf	X
192	1532	Primary Pol S1	X
193	1542	Fold Mirror	X
194	1562	BAMP entrance	X
209	1600	BAMP exit	X
210	1624	TSF Input Air Surf	X
212	1752	TSF East Pinhole	X
213	1756	Inj Mirror	X
214	1878	TSF Output Vac	X
216	1880	IR DBS S1	X
218	1900	IR HR 1	X
219	1904	IR HR 2	X
220	1922	VW S1	X
222	1930	IR HR 3	X
223	1962	G1	X
224	1982	G2	X
225	2044	G3	X
226	2066	G4	X
227	2108	DM2	X
228	2116	SPHR 1	X
229	2124	SPHR 2	X
230	2136	BC	X
231	2142	SPHR 3	X
232	2152	SPHR 4	X

Pos ID	Label	Time Delay
123	CSF Output Air Surf	942
124	CSF Output Vac Surf	944
126	CSF Input Vac Surf	1100
143	MAMP 4 out	1178
179	CSF UpWest Pinhole	1416

1828
2 pass
long
lower

Type desired RID

Nothing Selected

Figure 5.0: GUI Output with graphs and table of return signals.

Future Work

The next step for the OTDR project is to add features that allow the estimation of the magnitude of possible return signals. This will tell whether the return signals present a threat of damaging the laser.

Also, the same OTDR program built for the OMEGA EP laser will be implemented on the original OMEGA laser. Once the OMEGA laser components are entered into their own database, the program will do for OMEGA exactly what it is planned to do for OMEGA EP. Therefore, the program benefits both laser systems.

Conclusion

Reflected light from optical components in the OMEGA EP laser represents a significant barrier to the Laser Lab goal of supporting laser driven fusion research. It is minimized to an acceptable degree by anti-reflection coatings, but these coatings can wear out and fail over time. The OTDR program was created to be able to tell if an optical component is malfunctioning so that it can be isolated and replaced. By minimizing the reflections, light loss is minimized, meaning that the laser beam will hit the target at near full power, with no damage to the OMEGA EP laser.

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