Whitepaper

Excelitas Technologies White Paper on High Energy Laser Optics

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April 23rd, 2021

1.0 Overview

High Energy Laser (HEL) systems have become a reality in the military domain. As this technology continues to increase in Power output, the Optical Manufacturing industry will be pressured to produce optics with levels of performance and reliability that are not commonplace in the industry today. The system level characteristics of Beam Quality, Throughput, Reliability, SWaP and Cost will continue to be at the forefront of the discussions for the current and future generations of HEL weapons.

This paper walks through how the Specifications and Manufacturing Methods of the Optical Components in these HEL systems affect each of the system level characteristics. The purpose of this paper is to clarify to the Designer, Supply Chain Managers, Program Managers, and Material Buyers the options and tradeoffs available to them from an Optical perspective. The goal is to save time and money from a system design perspective through a more efficient understanding of what is possible.

1 Introduction

High Energy Laser (HEL) systems have been in development for many decades, but recently are gaining traction as a viable military tool. As modern weapons become more powerful, transportable, and effective, it is important first to understand how recent history has shaped the industry today.

In the early 2000s, the National Ignition Facility (NIF) program at the Lawrence Livermore National Labs demonstrated the extreme power that chemical lasers can generate, initiating the modern era of high-powered lasers. This system combines 192 lasers to achieve up to 500 Terawatts of peak power, enough to induce nuclear fusion reactions – the goal of the program. To this day, the NIF Laser remains the largest and highest-energy laser in the world [1].

In 2009, Directed Energy Systems and Northrop Grumman demonstrated a more transportable approach by combining seven 15kW electric lasers for the Joint High Power Solid-State Laser (JHPSSL) that achieved weapons-grade power of 105kW with very good efficiency and beam quality [2]. This program was key in proving that military-grade transportable systems were in fact possible, and sparked the industry to continue progressing the technology.

Entering the 2020s, Defense Contractors are focusing on demonstrating ever more powerful laser weapon systems. Examples of the intended function of these systems are as follows: to defend military bases or battleships from drone attacks, defend a high-profile plane from attack, shoot down ICMB and hypersonic ballistic munitions, protect satellites in orbit, and even for use in air-to-air combat. These applications and others will necessitate an extremely accurate and reliable laser system with increasing levels of power requirements. The key system level characteristics to consider as the technology moves forward are Beam Quality, Throughput, Reliability, SWaP and Cost.

The overall system can benefit from a better understanding of the optical components' impact from a manufacturing perspective, as controlling the components is the key to unlocking the best system performance possible. To achieve this, system level integrators will need work closely with their optics suppliers to understand best how to specify their components and sub-assemblies.

Excelitas Technologies Corp. has been involved with sub-components for high-energy lasers for decades, having manufactured HeNe lasers and optics for laser systems since 1993 as Research Electro-Optics, Inc. (REO) in Boulder, Colorado. REO's notable history includes commercializing the use of Ion Beam Sputtering (IBS) coating technologies for the most prolific Ring Laser Gyroscope systems in the world, as well as for extremely high-power industrial lasers. REO was a key optics supplier for both the NIF and JHPSSL programs, and continues to be involved with many next-generation high-energy laser systems. Recent testing on Excelitas HEL optics showed outstanding performance during a 150kw system test.

Excelitas Technologies Corp. acquired REO in 2018. Excelitas continues to operate at the forefront of optics manufacturing technology, and maintains the most robust understanding of Laser Induced Damage Threshold in the industry. This is the reason why Excelitas' optics continue to be the most reliable for high-energy laser systems, exemplified through continuous use in the NIF laser almost 15 years after inception.

2 System Characteristics

The critical Laser System Characteristics of High-Energy Laser systems are Beam Quality, Throughput, Reliability, and SWaP-C. These four characteristics play a large role in the overall effectiveness of the laser system performance.

2.1 Beam Quality

Beam quality refers to how "sharp" the laser spot is when the laser hits a target. Technically, it is how close the spatial distribution of the beam is to an ideal (usually Gaussian) beam. Better beam quality results in more energy in the beam and more power transmitted to the target. This impacts the performance characteristics of effective range, spot size, quality of the effect, and speed of the effect. There are factors such as distance to target, atmospheric turbulence and thermal blooming [3] that play into effect that can be out of one's direct control. Beam Quality can be influenced by tightly controlling the optical specifications Surface Figure and Absorption.

2.2 Throughput

The next critical aspect of high-energy laser systems is the Throughput of the system. Throughput is a measure of how much power the system can handle. A strong power source is meaningless if only a fraction of the power is transmitted through the system, so high Throughput yields higher power transmitted to the target. Throughput impacts overall performance characteristics of effective range, quality of the effect, speed of the effect, and size of the system. The optical specifications of Aperture Size, Reflectivity and Transmission, and Absorption play a large role in maximizing throughput. Laser Induced Damage Threshold must also be considered; optics will fail as Throughput increases, unless the optics are designed to withstand the energy.

2.3 Reliability

Potentially the single most important characteristic of an HEL System is its Reliability. If a system fails in the field, it can put many lives in danger. The length of time a system is expected to operate under intended use conditions is the main concern of many end users. Reliability influences the maintenance intervals needed, overall cost of use, and the environments in which it is effective. Optics tend not to be the cause for field failures, as optical failures are rarely latent failures. However, an understanding of an optic's stability can quantitatively be understood through measurements of Surface Quality inspection, Temperature and Humidity Sensitivity Testing, and Durability Testing.

2.4 SWaP-C (Size, Weight, Power, Cost)

As with any military system, Size, Weight, Power and Cost are important design considerations. With High Energy Laser systems, there is a general understanding that larger systems allow for lasers that are more powerful. Thinking of the NIF Laser system, this logic holds. The problem, however, is that these HEL systems must be mobile enough for battlefield situations. Depending on the application, it can be more (vehicle mounted) or less mobile (base defense), but the larger the system becomes, the more difficult to move and more power is needed to operate. Recent advances in fiber laser technology have allowed much smaller packages to produce much higher power lasers. This has helped reduce the overall size of many laser systems, but there is still a drive to have systems with exit apertures greater than 550mm. As these systems grow, so must all of the optics in the system in order to accommodate the larger beam size. With optics, the larger the parts get the more difficult and expensive it becomes to manufacture.

The following section describes the optical specifications that influence these system level characteristics. The manufacturing methods to achieve these optical specifications will be explored in a later section. The final section describes tradeoffs when prioritizing each system characteristic.

3 Optical Component Specifications

Optical Specifications heavily influence the laser system characteristics. The optical specifications to consider are Laser Damage, Surface Quality, Absorption, Spectral Performance, Stability & Durability, Aperture Size and Surface Figure. Each specification can influence one or more system characteristic, so it is necessary to understand the interplay between the specifications.

3.1 Laser Damage

Laser Damage, or Laser Induced Damage Threshold (LiDT), is the level of laser fluence that an optic can safely withstand without damage. Lasers are either Pulsed or Continuous Wave (CW), and the failure mechanisms are different between the two types. An example of a damage event is shown in Figure 1.

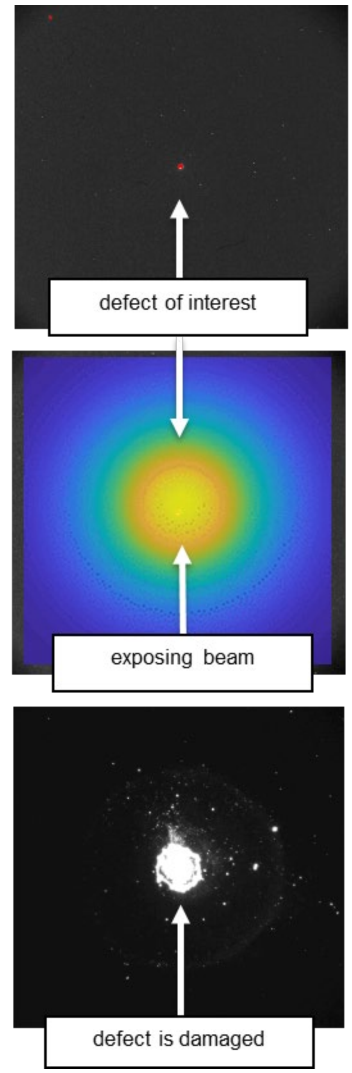


Figure 1. Laser Damage Example

For Pulsed lasers, the damage mechanisms of nonlinear absorption and multi-photon absorption are key. This has to do with the material's ability to pass electrons through the bulk material. If too many electrons are absorbed, a damage event occurs. The material's band gap, which strongly relates to the refractive index, is the main driver in the ability to pass electrons. The substrate and optical coating materials must be considered, which plays a heavy role in how thin film coatings are designed for these applications. *Figure 2* shows example bandgap values for various optical materials and the associated LDT.

Material	Bandgap (eV)	n	LDT (J/cm²)
Ge	0.7	4.4+0.15i	0.24
ZnSe	2.5	2.49	0.53
Ta_2O_5	4.1	2.1	2.2
HfO_2	5.3	1.9	3.4
Al_2O_3	6.5	1.65	4.2
SiO_2	7.5	1.46	6.3

λ = 1030 nm (1.2 eV)
τ = 500 fs

Gallais and Commandré
Appl. Opt., **53**, A186 (2014)

Figure 2. Bandgap of various material types.

For Continuous Wave Lasers, the dominant damage mechanism is through linear absorption, so thermal effects are key. The thermal conductivity of the bulk and thin film materials must be considered, and again influences what materials are chosen for a thin film coating.

However, even when the correct materials are chosen and the thin film design is optimized, laser damage events can still occur. The damage mechanism is the enhancement of E-field by the curvature of defect-initiated nodules that lowers the damage thresholds to below intrinsic values. Simply put, if the beam interacts with a defect, damage is more likely than on a defect-free spot on the surface. The sparse nature of defects makes the evaluation of laser damage over a surface a statistical challenge [4].

3.2 Surface Quality

Surface Quality is the optical specification that quantifies the level of defects on an optical surface. The "better" the surface quality, the fewer defects are present.

There is work being done to better understand how defects correlate to laser damage. It must be understood that there is never a zero chance of damage at any level of laser fluence, regardless of defect size [4]. Figure 3 shows an example of the probability of Damage events at various fluence levels.

In a separate Excelitas study, it was shown that a 10µm defect will initiate damage with approximately 50% probability at 50J/cm^2 in a typical HfO_2/SiO_2 High Reflector, illuminated with a 20ns pulse at 1064nm [5]. Figure 4 shows an example of probability of damage from high fluence over a surface. Note the profile tends to follow the Gaussian shape, as would be expected.

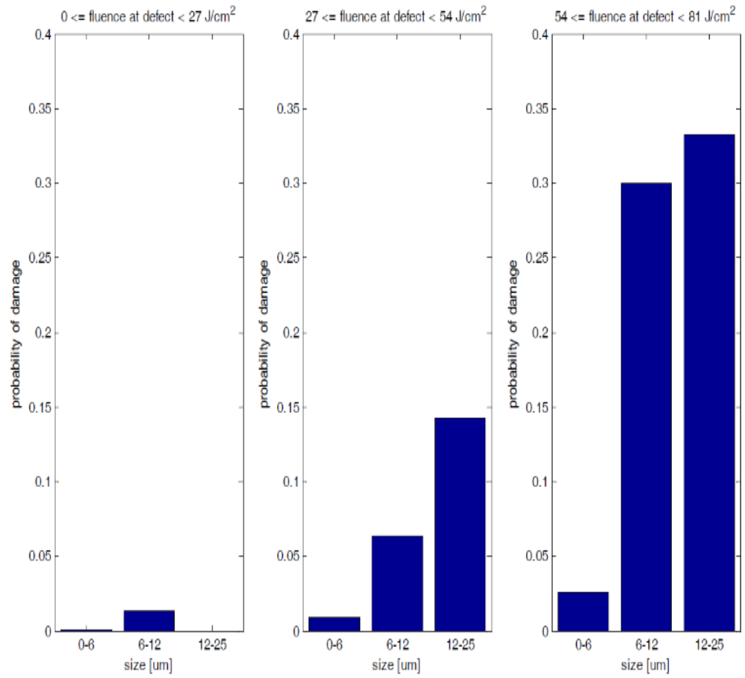


Figure 3. Probability of Damage Events at various fluence levels [1]

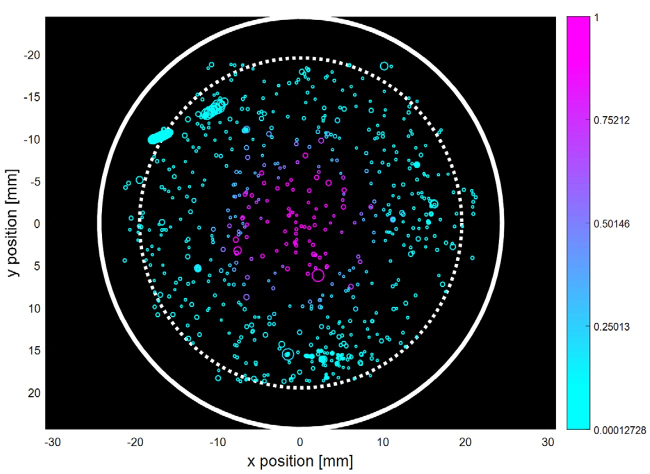


Figure 4. Damage location probability chart for high fluence laser optics

To give the best chance of not having a damage event occur on an optic, the optimal solution is to have zero defects on the optical surface. This is next to impossible to achieve in realistic manufacturing practices, but the goal is to minimize the amount of particles that are exposed to the component. Generally, as surface quality gets better, Laser Damage and Durability improve, but cost goes up.

Excelitas can offer the standard LiDT performance at various wavelengths shown below in Figure 5, depending on aperture size and material. Note that more robust specifications can be achieved, but the values shown are an expectation of baseline performance.

λ	Pulsed - 20ns		CW	
	HR	**AR**	**HR**	**AR**
1064nm	50 J/cm^2	30 J/cm^2	20 MW/cm^2	10 MW/cm^2
532nm	30 J/cm^2	15 J/cm^2	-	-
355nm	10 J/cm^2	5 J/cm^2	-	-

Figure 5. Common LiDT Performance at various wavelengths.

3.3 Absorption

An optic in a laser system can either reflect, transmit or absorb the light as it interacts with the optic. The goal with optics in high-energy laser systems is to absorb as little of that light as possible, particularly in Continuous Wave systems. Light gets absorbed either via the bulk optical material, through defects on the surface of the optic that cause the light to scatter, or by the materials that make up the optical coating [4, 6]. Minimum achievable absorption values at various wavelengths are shown below in Figure 6 for both High Reflector and Anti-Reflective coatings.

λ	HR	AR
1064 nm	1 ppm	3 ppm
940 nm	2 ppm	3 ppm
532 nm	10 ppm	20 ppm
355 nm	0.05%	0.07%

Figure 6. Minimum achievable absorption levels.

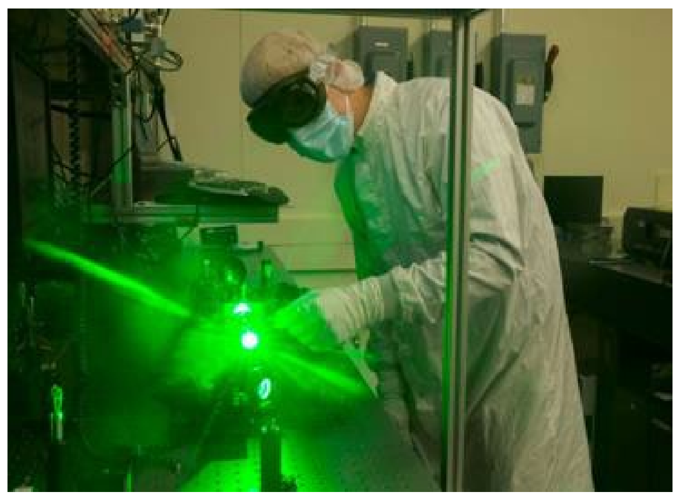
One of the main differentiating technologies in use to minimize absorption is IBS Coating technology. IBS Coatings can produce absorption levels down to 1ppm repeatedly, whereas an E-Beam coating would tend to be more in the 100ppm levels.

When working with absorption levels in the 1ppm level, non-standard measurement methods are required. The most sensitive method is called Photothermal Common Path Interferometry (CPI), which is sensitive down to 0.1ppm. While the accuracy of this system is ~20%, it is the best way to confirm absorption levels necessary for the best High Energy Laser optics. Other measurement methods' performance is shown in Figure 7.

Method	Accuracy	Sensitivity
Photothermal CPI	20%	0.1ppm
Calorimetry	1%	10ppm
Spectrophotometry	1%	1000ppm

Figure 7. Absorption measurement methods.

When absorption is optimized, Continuous Wave Laser Damage performance improves. Interestingly, Pulsed Laser Damage performance decreases, due to the materials used in the optical coating. It is very important to specify which type of system the optic will be used in, as the manufacturing process and materials are not the same depending on the use. Additionally, multi-spectral performance will decrease as absorption is optimized. This will be discussed more in the following section.



3.4 Spectral Performance

Reflection and transmission levels are extraordinarily important in High Energy Laser systems. As each optic will not reflect 100% of the incoming beam, there is a leaking effect where the beam power exiting the system could end up being dramatically lower than what came out of the laser source. This means lower power on target, and a less effective system.

For a single optic at a single wavelength, it is relatively easy to achieve a high reflector with up to 99.9995% reflectivity.

Take the example shown in Figure 8, which is a 33-layer Ta_2O_5/SiO_2 design. It has an average reflection of ~99.997% across the design region centered near 1064nm, Absorption of <2ppm, Design Thickness of ~5µm (resulting in a low stress coating, short run time, and cheaper coating), and a Surface Quality much better than 10-5. The resulting optic would have very good laser damage resistance and would perform extremely well for the primary band. This would be a great solution if the optic only needed to reflect a single band.

The issue is that most High Energy optics are designed to do more than just reflect the primary waveband; usually there are 3-4 different wavebands. This type of design requires compromises to reflectivity levels, absorption, and laser damage in order to be produced.

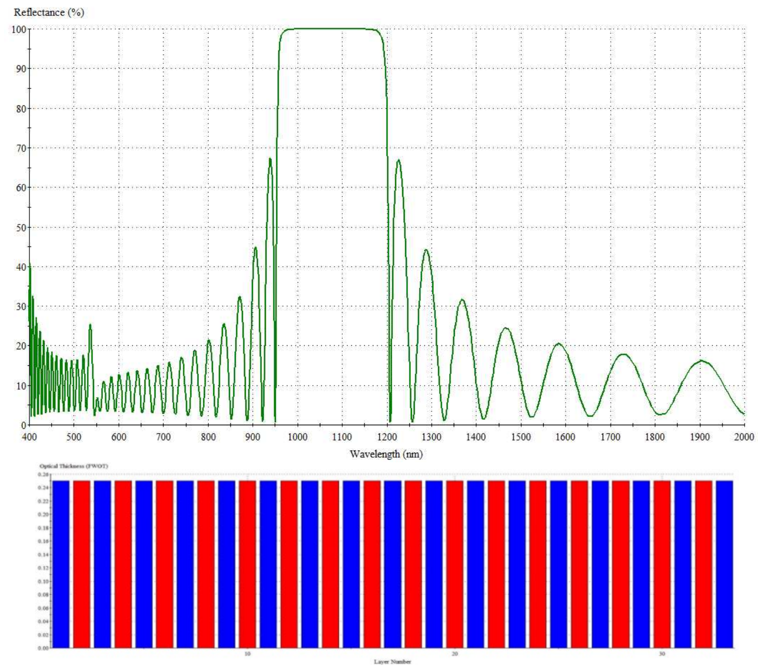


Figure 8. R% (above) and design (below) of a Single Band High reflector

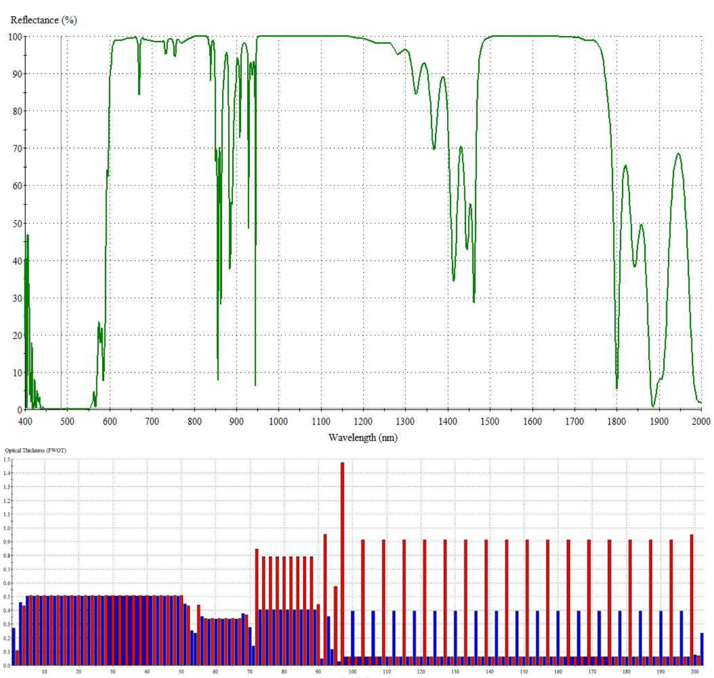


Figure 9. R% (above) and design (below) for multi-spectral high reflector.

Take the example shown in Figure 9 of a multi-spectral high reflector, which is a 200-layer Ta_2O_5/SiO_2 design. This has an average reflectance of 99.997% at the design wavelength near 1064nm, Absorption of ~20ppm, design thickness of 21µm (high stress, long run, expensive), and surface Quality around 20-10.

In order to optimize multi-spectral performance of this coating, the reflection levels of the other bands of interest must decrease, the overall laser damage resistance will be lower, and the surface figure control would decrease. This would be a very expensive optic, and generally will be very hard to produce repeatedly.

When specifying multispectral designs, it helps to prioritize bands clearly so if tradeoffs must be made during the thin film design, the manufacturer can do so appropriately. In addition, it helps to not over specify R% in secondary bands, as it will be very difficult to achieve high levels of performance across each band. Lastly, if transmission bands can be used in place of additional reflection bands, it tends to be easier to manufacture for multispectral coatings.

The alternate way to achieve performance with multiple wavelengths of interest is to create secondary systems that are boresight aligned to the primary system. This allows the primary optics to be optimized for best performance, while the secondary system gives up some performance in order to accommodate more functions. If a design tries to include too many functions in a single optical train, the coatings become almost impossible to manufacture, especially at volume.

Since there are multiple optical components in High Energy Laser systems, it is extremely important that all optics are transmitting or reflecting as much as possible on an individual basis for a given wavelength, as even one low-performing optic can reduce the entire system performance. Take the below chart, Figure 10, as a trivial example being considered at one wavelength for an eight optic system in reflection.

Number of Optics	8	8	8	8	8	8	8	8
% Reflection Avg.	95.000%	96.000%	97.000%	98.000%	99.000%	99.900%	99.990%	99.999%
System %R	66.342%	72.139%	78.374%	85.076%	92.274%	99.203%	99.920%	99.992%

Figure 10. Component Transmission quickly affects system Transmission

Notice how moving from an eight optic Average %Reflection of 95.0% to 99.0% raises the overall system %Reflection by almost 26 percentage points. From a different perspective, the difference between an eight optic average Reflection of 99.9% to 99.999% is only a 0.789 percentage point increase in system performance.

The key here is that after a certain point, there are diminishing returns when trying to squeeze out slightly better reflection on each optic. If system designers work with Excelitas during the design phase, we can help to suggest specifications for each optic that will allow for the optics to overall be cheaper, better performing, and more easily made in volume.

3.5 Stability and Durability

The stability and durability of an optic refers to the degree of exposure to abrasion, humidity, thermal shocks, etc. that an element can withstand without damage. The factors that play into this stability are coating materials, raw material CTE, and coating process. This level of stability and durability can be quantified through various measurements and tests.

For stability, the goal is that an optic can be exposed to various environmental conditions without impacting optical performance. The main environmental factors to consider are temperature and humidity changes.

For humidity, the first metric that quantifies stability is known as the “approximate humidity shift”, also known as “Wet/Dry shift”. When optics are exposed to high humidity, there can be a shift in optical performance due the chemical sensitivity of the materials. The reflection and transmission performance is measured before and after humidity exposure, any spectral shift change is the resulting metric.

“Pin holes” or process defects in a coating can cause small spots in the coating to be more susceptible to humidity absorption, leading to reduced reliability. Through Surface Quality inspection, this reliability can be quantified. E-Beam coatings are more susceptible to this defect, as small pin-hole defects are inherent to this coating type. IBS coatings are more durable because they do not have these defects.

Concerning temperature stability, most coating materials are resistant to thermal changes up to the phase change temperatures. E-Beam coatings are generally applied at temperatures well above any normal system operating temperature, so once the optics have cooled, they are quite stable. IBS Coatings are applied at room temperature, but they are still very resistant to temperature changes.

Any temperature sensitivity an optic may experience is generally due to differential thermal expansion coefficients between the substrate and the coating. If the stress relationship changes between the coating and the substrate, small cracks can form in the coating. This phenomenon is known as crazing, an example shown to the right in Figure 11. Crazing is more common in coatings with Tensile stress, which is possible with E-Beam coatings. These cracks appear when the differential stress exceeds the tensile yield strength of the coating. For IBS coatings, this is not a common failure, as the coatings all impact a Compressive stress on the optic. The stress is quantified through surface figure measurements, so an optical coating's relative stability can be readily understood.

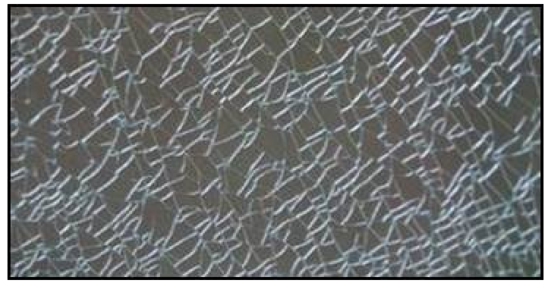


Figure 11. Example of crazing in a coating.

3.6 Aperture Size

The aperture size refers to the size of the element and the fraction of its area that is filled by the beam. The larger the aperture, the better the beam quality and the higher the throughput. Large apertures are required for some of the very highest power HEL systems, but this larger size usually comes with much higher cost and weight.

With Optics, the cost increases proportionately with the surface area of the part; larger means more expensive. This is because the material itself is more expensive, the fabrication is more difficult, and the optical coating chamber capacity is reduced, among other factors. Large optics can also require special equipment to manufacture and usually require custom tooling to hold or move the optics without damaging them.

Figure 12. Example of large, lightweighted optic.

Obtaining optical grade material properties across a very large material boule is difficult for many materials, so the cost will inherently go up. Additionally, there are IR materials that cannot be grown above specific sizes, so it is best to consult with your optics supplier about what is possible early in the design and what material you intend to use. Many large optics tend to employ lightweighting features to make them easier to handle without losing rigidity properties, but these bring myriad other issues with controlling surface figure as well as adding additional cost.

For fabrication, it is harder to maintain good surface figure and surface quality across a large optical surface. The machinery required to manufacture can have size restrictions, so custom machinery is required for large optics. A factor to consider is that just because an optics supplier is good at small components, it does not mean they will be good at making large components. It is best to consult with the fabrication shop about what sizes they commonly manufacture.

For coating, there is a similar size restriction with machinery. However, assuming the optic can fit in a coating chamber, the costs still scale with the area of the part. The larger the optic, the smaller the batch size. The smaller the batch size, the higher the cost. Large optics also require special tooling to lift and place the optic into a coating chamber as well as off-set weights that may be necessary to balance the crucible inside the coating chamber that holds the parts.

3.7 Surface Figure

Surface Figure refers to how accurately an element matches its nominal surface *shape*. Surface Figure affects Beam Quality and Throughput from a system level perspective. Surface Figure plays a role in both transmissive and reflective optics, and is one of the largest cost drivers in optical manufacturing.

Surface Figure can be controlled very tightly, both in fabrication and coating processes. However, the tighter the Surface Figure requirement, the more difficult it will be to make and more expensive the optic will be. There are myriad factors that impact Surface Figure, but the biggest cost driving factors are substrate material type, size, coating stress, and lightweighting features. Depending on the combination of factors, the Surface Figure specification may be extremely difficult to achieve. There are various fabrication methods to control Surface Figure, which will be discussed in detail in later sections. In coat, there are techniques such as back-side stress compensation coatings, stress relief with high temperature baking, or having a "pre-figured" surface that becomes "flat" when the coating is applied.

The images below in Figure 13 (left to right) show pre-coat, post-coat, and post-coat-bake surface figure maps of the same optic. These images highlight the difference between Power, PV, and RMS specifications. Note a Negative Power value indicates a "Convex" shape in this measurement. These pictures also highlight that the Surface Figure changes dramatically throughput the manufacturing process. Understanding how to control this change is key to being able to produce optics with good Surface Figure.

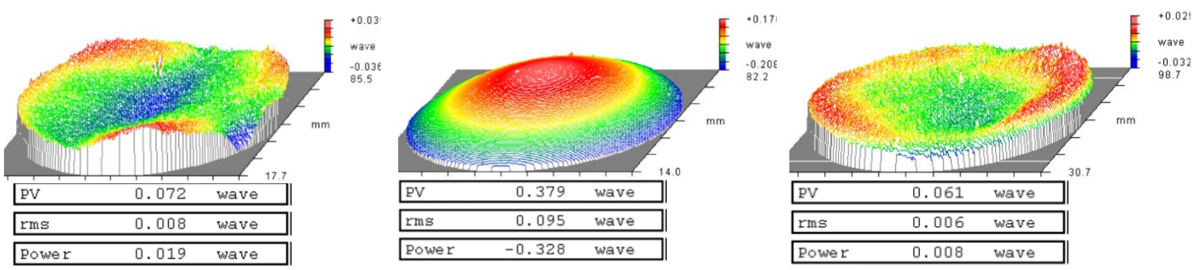


Figure 13. Surface Figure measurements of pre-coat (left), post-coat (middle) and post-coat bake (right).

It should be understood that just because all surfaces in a system are "flat", it does not mean the beam quality and throughput will necessarily be good, because other factors come into play. The main take away should be that as aperture size increases or coating complexity increases, it becomes significantly more difficult to control Surface Figure.

4 Materials and Optical Manufacturing Methods

The Materials chosen and Optical Manufacturing Methods employed determine the level of performance of each Optical Specification. Each Method affects more than one optical specification, so an entire understanding of the processes from raw material to final optical coating is required in order to produce a reliable and repeatable result.

4.1 Substrate Material

There is no one single material that is "best suited" for High Energy Laser applications. Each material has its tradeoffs and best use cases. Depending on the spectral performance needed, many materials are not suitable right from the start, while others may not be able to take advantage of certain Coating technologies. The four most commonly used substrate materials in High Energy Laser systems are Fused Silica, Silicon, Silicon Carbide, and Aluminum.

Fused Silica (Figure 14) is an optically pure and transparent material with excellent properties for polishing. It is good for transmissive components and smaller mirrors. It is a very common material and most optical manufacturers can machine it. It is machined using traditional polishing techniques. It can produce the lowest surface roughness and has outstanding thermal expansion properties.

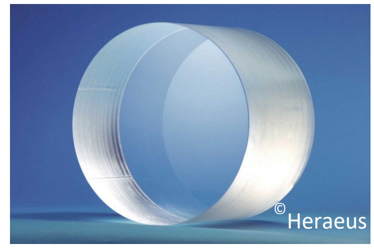


Figure 14. Example of a Fused Silica optic.

Figure 15. Example of a Silicon optic.

Silicon (Figure 15) has excellent thermal and mechanical properties and is suitable for high quality polishing. It can be diamond turned or machined using traditional optical manufacturing methods. It has very good thermal conductivity and expansion properties, and as such is a great high-fluence mirror.

Silicon Carbide (Figure 16) has outstanding thermal and mechanical properties for lightweighted optics. However, it is extremely challenging to polish due to its Hardness and only a few companies can manufacture it. It gets expensive very quickly, but it is great for high performance mirrors that need complex lightweighting.

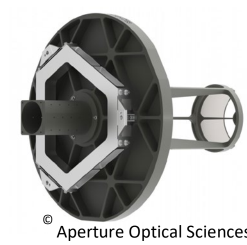


Figure 16. Example of a Silicon Carbide Optic.

Figure 17. Example of an Aluminum optic.

Aluminum (Figure 17) is easy to machine and has excellent thermal conductivity, but has poor properties for optical polishing. It is cheap and conducts heat well. It is generally used as a mirror that does not need outstanding optical capabilities.

Typical property values of each material type is shown below in Figure 18. Note that there is not one "ideal" material for High Energy Laser systems, each optic serves a specific use and should be designed accordingly. Silicon, however, should be considered a very good "middle of the road" material that is suitable for many High Energy Laser applications.

Property	Typical Values			
	Fused Silica	Silicon	Silicon Carbide	Aluminum
Specific Modulus	25 MPa-m^3/kg	60 MPa-m^3/kg	140 MPa-m^3/kg	25 MPa-m^3/kg
Hardness	522 kg/m^3	1100 kg/m^3	2800 kg/m^3	120 kg/m^3
Roughness	<0.5A rms	1A rms	3A rms	~20A rms
CTE	1ppm/°C	2.6 ppm/°C	4 ppm/°C	23 ppm/°C
Thermal Conductivity	1.4 W/m-K	148 W/m-K	300 W/m-K	215 W/m-K
Cost	$$	$$	$$$	$

Figure 18. Typical Substrate Material Properties for commonly used HEL material.

4.2 Polishing and Finishing Methods

There are various Polishing methods available to achieve desired specifications, depending on the requirements, shape, and form factor of each optic. Each of these processes is utilized for a specific reason, so the more information that can be given to the optical supplier during the quote phase, the more custom-tailored the manufacturing process can get. The outcome of the polishing process influences Surface Figure, Surface Quality, and Surface Roughness; all specifications that highly influence HEL optical performance, as discussed.

Figure 20. Example of Conventional Pad Polishing.

Conventional Pad Polishing (Figure 20) is a full-aperture polishing process using loose abrasive slurry and polyurethane pads in a spindle, lap, or CNC machine configuration. It is best suited for medium-quality spherical or aspheric components. It can produce excellent surface quality and is relatively fast to complete.

Pitch Polishing (Figure 19) is a full-aperture polishing using loose abrasive slurry and formed natural or synthetic pitch, in a spindle or lap configuration. It is best suited for very high fluence components. It is a slow process, but it produces extremely low surface roughness and excellent surface quality. An extension of this is known as "Super Polish", that produces <0.5Angstrom rms surface roughness.

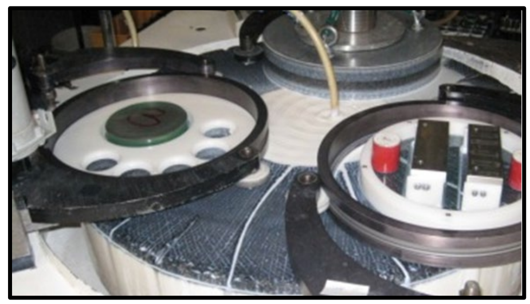


Figure 19. Example of Pitch Polishing.

Figure 21. Example of Robotic Polishing.

Robotic Polishing (Figure 21) is sub-aperture polishing using a small pad tool controlled for precise, laterally deterministic material removal. It is not a full aperture polish, but allows for deterministic and repeatable Surface Figure control. It is best for freeform or off-axis components. It is a decent way to make lenses, but cannot compete with a Pitch Polish surface finish. It leaves a trace in mid-spatial surface figure frequencies.

Magnetorheological Finishing Polishing, commonly known as MRF, is a sub-aperture finishing process using magnetically shaped loose abrasive slurry for precise and laterally deterministic material removal (Figure 22). MRF is best suited for figure-critical components and is used to correct Wavefront errors. It is not a standalone polishing process, and is best used in conjunction with Pitch or Robotic Polishing. It is a very fast process and leaves a great surface quality with decent surface roughness.

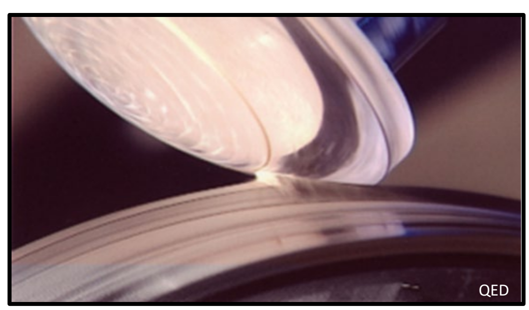


Figure 22. Example of MRF Polishing.

Typical property values are shown below in Figure 23 for each polishing process.

Property	Typical Values			
	Conventional Pad	Pitch	Robotic	MRF
Figure Flexibility	Flat, spherical, on-axis asph	Flat, spherical	Arbitrary	Arbitrary
Efficiency/Cost	Fast (~ 1hr)	Slow (~ 6-8 hrs)	Varies	Fast (<1hr)
Mid-Spatial Freq	Essentially Zero	Essentially Zero	Some tool print-through	Some tool print-through
Surface Quality	"0-0" (5/ 2 x 0.016)	"0-0" (5/ 2 x 0.016)	10-5	10-5
Roughness	~ 3A rms	< 0.5A rms	~5A rms	2A rms
Subsurface Damage	~ 10um	-	~10um	-

Figure 23. Polishing methods typical values.

The main take away from this is that depending on the specifications on the drawing, the manufacturing shop will choose the polishing method to match. If a specification that drives that decision (Surface Roughness, Surface Figure, or Surface Quality) is over specified on a drawing, it could lead to unnecessary cost and lead time added to the optics.

4.3 Thin Film Coating Methods

A high quality Optical coating is a critical aspect in a High Energy Laser system as it is the conduit for reflecting or transmitting the energy through the system at the correct wavelengths. The optical characteristics that are most important in an HEL specific coating are absorption, scatter, repeatability, abrasion resistance and the ability to validate the coating's performance. There are four main technologies used to produce Optical Coatings: E-Beam/Thermal Evaporation, Plasma/Ion-Assisted Deposition, DC/RF Magnetron Sputtering, and Ion Beam Sputtering. There are preferred use cases for each technology, as each has its own strengths and weaknesses.

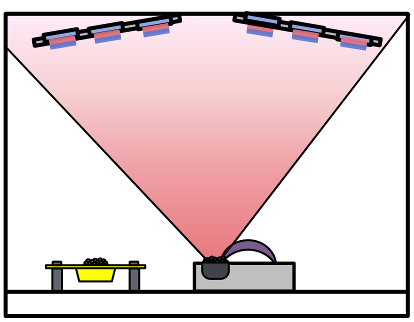


Figure 24. Depiction of E-Beam coating process.

E-Beam/Thermal Evaporation (Figure 24) is a simple, inexpensive process with a wide selection of materials and chamber sizes. It works by evaporating the desired material into a vacuum that then condenses on the optics. It is good for large parts with lower power density and is generally used for IR or DUV bands. The stress imparted on the optic can be either tensile or compressive, but it is a low stress. There coatings have high absorption and low durability, but good spectral performance.

The Plasma/Ion-Assisted Deposition process (Figure 25) is an extension of the Thermal Evaporation process, where an Ion Gun is placed in an E-Beam chamber and "assists" the evaporated particles hit into the optics with higher force. It creates a more dense coating than Evaporation on its own. It is good for large parts that need a higher laser power or have stress challenges, but the absorption will be higher than ideal for CW laser systems.

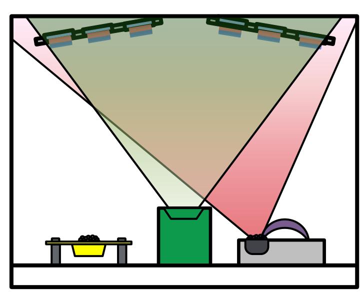
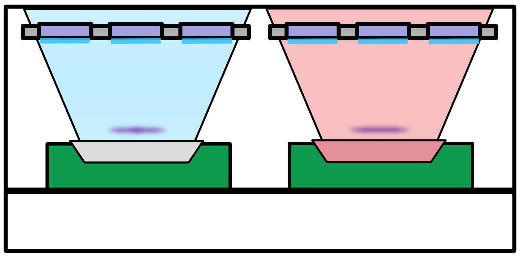


Figure 25. Depiction of Plasma/Ion-Assisted Evaporation Process.



The DC/RF Magnetron Sputtering process (Figure 26) uses energetic plasmas to sputter material from targets. It has a high rate of deposition and large chamber capacities. It is good for general purpose optics, is a high quality coating and is relatively cheap. It is also a durable coating, but has higher than desirable absorption for CW laser systems and it can be challenging to achieve great surface quality with these coatings.

Figure 26. Depiction of DC/RF Magnetron Sputtering Process.

The Ion Beam Sputtering coating process (Figure 27) uses a high-energy ion beam to sputter material from targets. It produces a very dense, high purity film that is optimal for High Energy Laser applications. It has unmatched surface quality and durability characteristics. The downside is that the coating imparts a large amount of Compressive stress onto the optic, so back side stress compensating coatings are common. This poses an issue with lightweighted optics, as there is not a coplanar surface to coat, so generally these types of optic must be pre-figured using MRF technology to compensate for stress. IBS Coatings have the highest power density and is optimal for the most critical components.

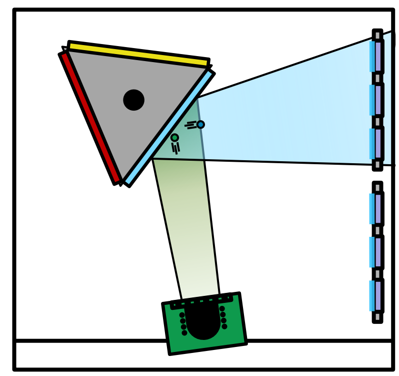


Figure 27. Depiction of Ion Beam Sputtering Process.

IBS is a largely automated method, so once the process is refined and established, it is highly reproducible. In contrast, evaporative methods require frequent changes in the coating chamber environment and control processes, such as source material replenishment, making it more difficult achieve a consistent HEL optic. See below in Figure 28 for a comparison of typical property values from each coating process.

Property	Typical Values			
	E-Beam/Thermal Evaporation	**Plasma/Ion-Assisten Dep**	**DC/RF Magnetron Sputtering**	**Ion Beam Sputtering**
Accuracy/Control	1%	0.5%	0.2%	0.1%
Deposition Rate	0.7nm/s	0.5nm/s	0.5nm/s	0.1nm/s
Stress	50MPa (T or C)	100MPa (C)	100MPa (C)	400Mpa (C)
Surface Quality	20-10	10-5	10-5	"0-0" (5/ 2 x 0.016)
Stability/Durability	Low	Medium	High	Highest
Absorption	100ppm	20ppm	20ppm	2ppm

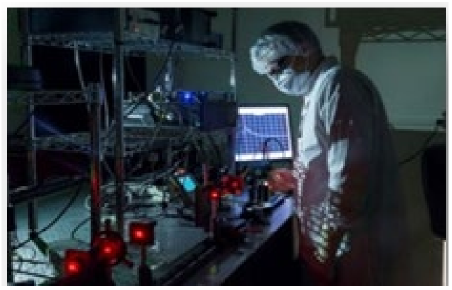
Figure 28. Typical Process values for various coating processes.

The main takeaway is that while there are many coating technologies available, IBS Coating is the differentiating technology that enables optics to achieve performance levels required for the highest power High Energy Laser systems.

4.4 Metrology

Assurance of ultra-reliable HEL optics requires the metrology to ensure process optimization as well as the components' compliance to specification. The Excelitas team is highly proficient in all aspects of optical component and assembly metrology and are able to certify meeting final requirements internally. For additional information, refer to the cited publications posted on the Excelitas website, which detail Excelitas and REO's efforts in developing metrology processes, specifically defects and laser damage metrology for high-energy laser optics.

REO developed its own internal automated LiDT Testing System that produces detailed information on damage events, including spatial location and sizes Quality [4, 7, 5, 8]. We are working on developing non-destructive LDT certification using a Dark Field Microscope and statistical models. We are working to develop a better surface quality certification method using Cavity Ringdown, TIS and Autmated Surface Quality Inspection (ASQI) tools.



REO IBS Coating capabilities combined with our high sensitivity metrology techniques enable the lowest coating absorption possible, further enhancing reliability and very high laser damage resistance. We have metrology tools that can take measurements at 1064, 940, 633, 532 and 355nm wavelengths. In addition to industry standard optical and spectral instrumentation, below is a partial list of in-house testing we regularly perform:

- In-house laser damage testing systems optimizing coating and surface processes
- Defect-to-damage correlation
- Automated Defect Measurements with unique enhanced diagnostics
- High Sensitivity Absorption Testing (Photothermal Common-Path Interferometry and calorimetry)
- Surface Metrology: Phase and white light interferometry, stylus profilometry, phase contrast microscopy (DIC)
- Optical Loss Measurements: Cavity ringdown at multiple laser wavelengths, custom measurement capabilities
- Automated exposure and data collection
- Spectral Measurements: UV to LWIR spectrophotometry, laser-based photometry
- Group Delay Dispersion
- Thin Film thickness and index
- Optical System Testing
- Multi-sensor Coordinate Measuring Capabilities

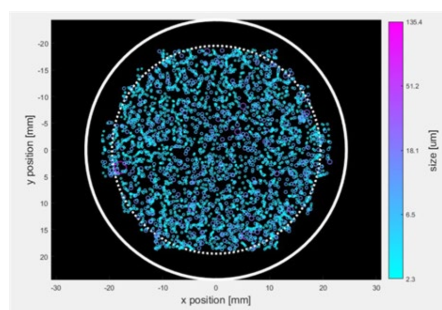


Figure 29. Example of Induced Laser Defect Mechanisms Metrology.

5 Tradeoffs

A major consideration for system design is to understand that an “ideal optic” is effectively impossible to manufacture. There are necessary tradeoffs that occur as part of the optical manufacturing process that limit the system level performance. Each specification is a function of many variables, and occasionally there are unintended consequences of trying to “optimize” for a single performance factor. With so many tradeoffs, it is best to discuss system needs as early as possible in the design phase with your manufacturing partner to ensure the desired design outcomes are not constraining your options or increasing your cost. Many times a simpler and more elegant solution can be found if the design intent is understood from the beginning.

In the below examples, the Blue arrow means a specification “gets better”, the yellow arrow means a specification “gets worse”, and the grey arrow means there is a “side-effect improvement” due to the combination of factors. These examples attempt to describe the complex interaction between the various optical specifications.

5.1 Throughput

When prioritizing Throughput for an optic (Figure 30), we will want to have the lowest Absorption and highest laser damage resistance possible. This will lead to a very stable and durable coating, so the reliability will improve. We also will want the highest Reflectance and Aperture size possible. This means we will want the best quality films and to have a large diameter optic. This will generally make Surface Figure harder to control and the system will need to be larger.

The difficult figure control will cause the beam quality to degrade, but as absorption is improved, the stability of the optic will improve because there will be fewer thermal effects. As aperture size goes up, the cost will increase for all aspects of the manufacturing process.

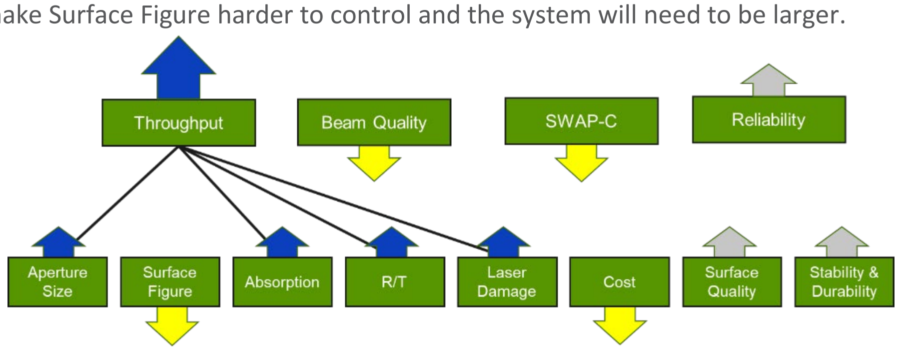


Figure 30. Tradeoffs when prioritizing Throughput

5.2 Beam Quality

If Beam Quality is prioritized (Figure 31), we will want the maximum possible aperture size and best Surface Figure possible. The Surface Figure will be a major cost driver here, as it is hard to maintain on large surfaces. We also will want to maximize absorption to minimize thermal effects, but will likely trade some Reflection and Transmission performance to achieve. The cost is the largest negative impact from this, as controlling Surface Figure is one of the more expensive processes in optical manufacturing.

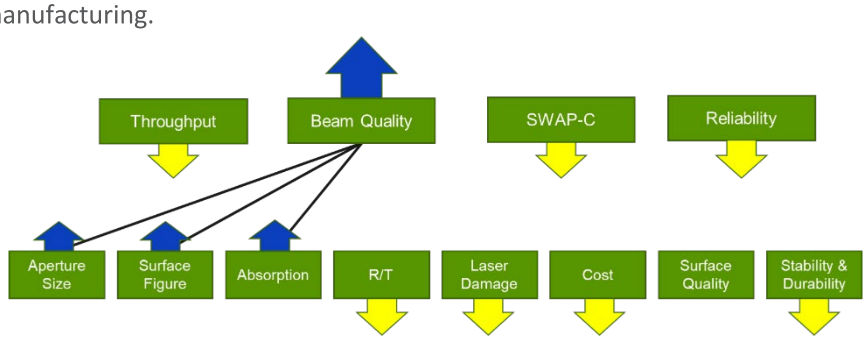


Figure 31. Tradeoffs when prioritizing Beam Quality.

5.3 SWaP-C

If Size and Cost, are prioritized (Figure 32) we will want to shrink the aperture size. This will give up some performance in beam quality, but if we increase the Reflection and Transmission performance, the impacts to Throughput are minimized. The surface quality can be maintained at a high level due to the smaller aperture size. Shrinking the aperture but increasing component requirements can result in an overall cost benefit as larger aperture optics are such a major cost driver.

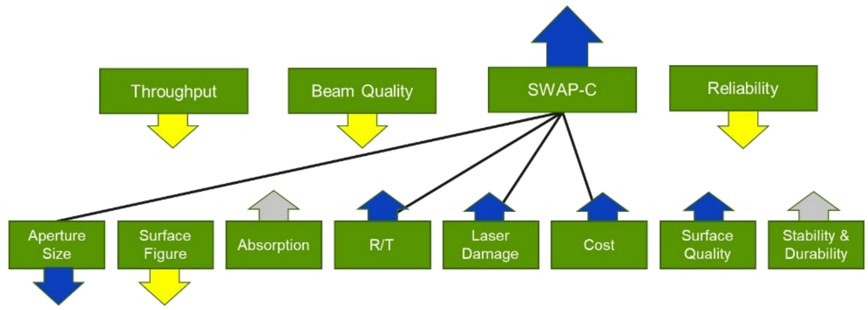


Figure 32. Tradeoffs when prioritizing SWAP-C.

5.4 Reliability

If Reliability is prioritized (Figure 33), it will tend to only make the system perform better. We will want to prioritize laser damage, surface quality, and durability. This can be achieved by using the highest quality film possible. A result of that will be improved absorption characteristics and higher throughput, but the cost will increase.

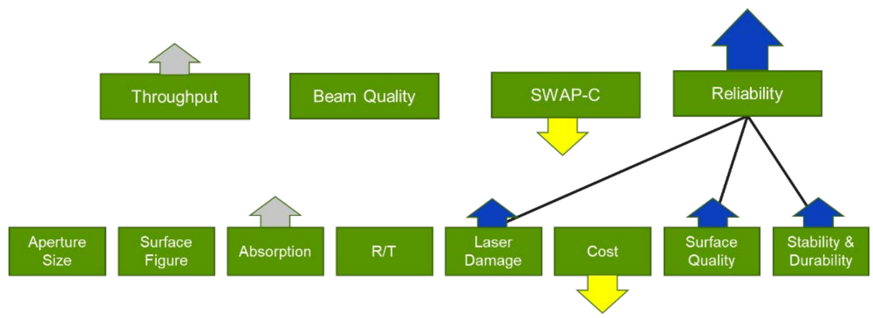


Figure 33. Tradeoffs when prioritizing Reliability.

6 Conclusion

It is important to understand that specifying optical component characteristics is key to optimizing laser system performance. It is not required that designers understand all of the aspects of these tradeoffs and impacts, but understanding the critical factors is helpful in order to make the most informed decisions. A few minor specification changes can result in increased performance, lower cost, and a more reliable system.

6.1 About Excelitas Technologies

Excelitas Technologies® Corp. is a photonics technology leader focused on delivering innovative, high-performance, market-driven solutions to meet the lighting, optronics, detection and optical technology needs of our OEM customers.

Excelitas has proven design and manufacturing capabilities for market leading High Energy Laser optics, coatings and assemblies. We have an established history in the design and manufacture these items for many of the US primes and subassembly suppliers in the High Energy Laser market. Our products are trusted to perform by the most demanding High Energy Laser users in the United States.

Serving a vast array of applications across biomedical, scientific, safety, security, consumer products, semiconductor, industrial manufacturing, defense and aerospace sectors, Excelitas stands committed to enabling our customers' success in their end-markets. Our photonics team consists of 7,000 professionals working across North America, Europe and Asia, to serve customers worldwide.

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