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Analysis of laser damage tests on a coating for broad bandwidth high reflection of femtosecond pulses

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Abstract

We have designed and produced an optical coating suitable for broad bandwidth high reflection (BBHR) at 45^o angle of incidence (AOI), P polarization (Ppol) of petawatt (PW) class fs laser pulses of ~ 900 nm center wavelength. We have produced such BBHR coatings consisting of TiO_2/SiO_2 layer pairs deposited by ion assisted e-beam evaporation using the large optics coater at Sandia National Laboratories. This paper focuses on laser-induced damage threshold (LIDT) tests of these coatings. LIDT is difficult to measure for such coatings due to the broad range of wavelengths over which they can operate. An ideal test would be in the vacuum environment of the fs-pulse PW use laser using fs pulses identical to of the PW laser. Short of this ideal testing would be tests over portions of the HR band of the BBHR coating using ns or sub-ps pulses produced by tunable lasers. Such tests could be over ~ 10 nm wide wavelength intervals whose center wavelengths could be tuned over the BBHR coating's operational band. Alternatively, the HR band of the BBHR coating could be adjusted by means of wavelength shifts due to changing the AOI of the LIDT tests or due to absorbed moisture by the coating under ambient conditions. We conduct LIDT tests on the BBHR coatings at selected AOIs to gain insight into the coatings' laser damage properties, and analyze how the results of the different LIDT tests compare.

Key words: Optical coatings, broad bandwidth high reflection, high laser-induced damage thresholds.

Introduction

The context of this paper is large-scale petawatt (PW) class high intensity lasers whose pulses are of durations in the fs regime.[1] These pulses are comprised of broad spectral ranges of frequency components whose relative phases determine the pulse shape.[2] Our particular interest is in an optical coating suitable for broad bandwidth high reflection (BBHR) at 45^o angle of incidence (AOI), P polarization (Ppol) of PW class fs laser pulses of ~ 900 nm center wavelength, such as produced by the Vulcan Laser at the Central Laser Facility in the United Kingdom.[3] These BBHR coatings are important for reflection of the high intensity fs PW pulses by the final off-axis parabola and fold mirrors of PW lasers. The laser-induced damage threshold (LIDT) of the BBHR coatings must be high enough to ensure the mirrors will perform in the environment and under the laser pulse conditions of the actual PW laser beam train. This means that LIDT tests of the BBHR coatings play a critical role in determining whether they are suitable for use. We will explore some of the issues associated with LIDT tests of BBHR mirror coatings for fs pulses, focusing in particular on differences between the PW use laser and LIDT test laser environments, pulse durations, and wavelengths.

Dilemmas in LIDT tests of BBHR coatings

A major dilemma in LIDT testing of BBHR coatings is that available LIDT test lasers and test environments often do not match PW use lasers and their use environment. We discuss first the issue of environment. PW use laser beam trains just prior to final focusing of the high intensity fs pulse are in a vacuum environment.[1] The high power fs pulse fluences would otherwise lead to deleterious nonlinear effects in the transmission medium of any other ambient pressure environment. On the other hand, available LIDT test environments are often ambient, in air at room temperature, atmospheric pressure, and ambient relative humidity (RH). The LIDT laser beam is focused and its diameter remains large enough to keep fluences below thresholds for nonlinear effects in the air until just at focus, at the surface of the coated substrate undergoing the LIDT test, where self-focusing or intensity clamping may occur. The environmental issue is that the transmission (or reflection) spectrum of BBHR coatings may shift to longer wavelengths in ambient environments. This is due to absorption of water from the humid ambient environment by the coating, which is especially the case for BBHR coatings deposited by e-beam evaporation because such coatings are of relatively low density and high porosity, allowing them to more readily absorb water from ambient humid air. We present examples of such spectral shifts later in this paper for the two BBHR coatings of this study. As a result, the HR band of the coating under ambient conditions may no longer match its design HR band. This means that it no longer matches the spectrum of the PW use laser's fs pulse. So, while it is usually a goal for an LIDT test laser to have a pulse spectrum that matches that of the PW use laser, realizing that goal is of little or no value if the LIDT tests are done in an ambient environment in which the HR band of the BBHR coating has shifted beyond the fs pulse spectrum.

This leads to the second issue in LIDT testing of BBHR coatings, the issue of mismatch between center wavelengths and spectra of the pulses of available LIDT test lasers and of the fs PW use lasers as well as the HR band of the BBHR coatings. This is illustrated in Fig. 1 for scenarios of a PW use laser with 25 fs pulses at a center frequency, ν_0, and corresponding center wavelength, λ_0, and 25 fs, 300 fs and 1 ns LIDT test laser pulses, some of whose center frequencies/wavelengths match ν_0/λ_0 while others do not. For our illustration, we assume near Gaussian temporal profiles for the PW use laser and LIDT test laser pulses as depicted in Fig. 1(a). Possible corresponding frequency and wavelength spectra of these pulses are depicted in Figs. 1(b) and 1(c), respectively. This assumption of near Gaussian temporal profiles of the pulses is reasonable, but means that we are not illustrating situations in which the fs PW laser pulses exhibit skewed temporal or spectral profiles due to gain compensation or frequency chirping pulse shaping techniques.[2]

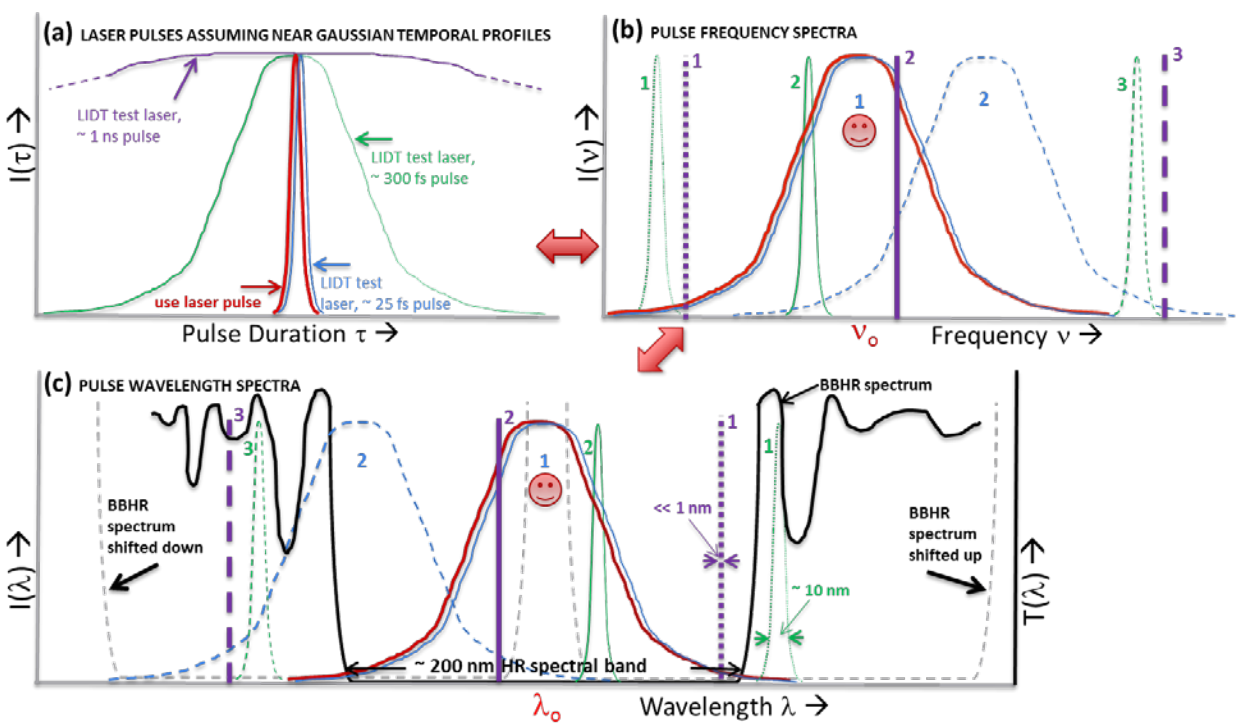


Figure 1: Illustrations of (a) a 25 fs PW use laser pulse of center frequency/wavelength, ν_0/λ_0, and LIDT test laser pulses of 25 fs, 300 fs, and 1 ns durations; (b) frequency spectra with various center frequencies for these pulses; and (c) wavelength spectra counterparts to the frequency spectra, as well as the transmission spectrum of a BBHR coating with ~ 200 nm HR band centered at λ_0 and also shifted up and down in wavelength.

Consider the scenario of LIDT test lasers with 25 fs pulses. This would be the ideal LIDT test situation in that it allows testing the laser damage properties of the BBHR coating with pulses of duration that match that of the PW use laser. Laser damage with such pulses would be primarily intrinsic, associated with multi-photon ionization mechanisms due to direct interaction of the high intensity fs pulse photons with the coating layer materials.[4] We show two cases in Figs. 1(b) and 1(c): case 1 in which the LIDT test laser pulse spectrum exactly overlaps that of the fs PW use laser and also the HR band of a BBHR coating, whose transmission spectrum, having a ~ 200 nm HR band, is depicted in Fig. 1 (c); and case 2 in which the LIDT test laser pulse spectrum is shifted to a higher center frequency (lower center wavelength) than that of the fs PW use laser or the HR band of the BBHR coating. For case 1 to occur would be very fortunate, since it is rare that an available LIDT test laser has pulses as well as center wavelength that exactly match those of the fs PW laser. Case 1 would mean that the entire spectrum of the fs pulse overlaps within the coating's HR band. For standard quarter-wave HR coatings, the E-field behavior for incident light of wavelengths within the central zone of the HR band is characterized by the intensity peaks that quench rapidly into the coating layers.[5] Near quarter-wave HR coatings also exhibit this E-field behavior. Quenching of E-field peak intensities into the coating persists out to wavelengths near its HR band edge but in a more gradual way, with appreciable intensities occurring deeper within the coating layers. Examples of these E-field behaviors for the BBHR coating design of this study appear later in the paper. Such quenching of E-field intensity into the coating is favorable to higher LIDTs because only a fairly small number of outer coating layers encounter high E-field intensities. But, as we have pointed out in the previous paragraph, even case 1 does not ensure valid LIDT tests of the BBHR coating if they are performed in a humid environment in which the HR band shifts with respect to the fs pulse spectrum. This latter situation is similar to case 2 described above. In both of these examples, the test laser pulse has part of its spectrum at wavelengths for which the BBHR coating exhibits high transmission. LIDTs in tests of a BBHR coating with such offsets between the laser pulse spectrum and the coating's HR band will be lower than when the center wavelengths of the pulse and the HR band of the coating match. This is because, when the center wavelengths are offset, only a part of the pulse spectrum probes the coating's HR band while the other part probes the coating at wavelengths of high transmission outside its HR band, thus penetrating at moderate to high electric field intensities all the way through the coating layers and resulting in increased likelihood of laser damage. Therefore, it is important in laser damage tests for the pulse and coating HR band center wavelengths to be the same or nearly the same in order to avoid obtaining misleadingly low LIDTs.

Figure 1 also shows examples of 300 fs and 1 ns LIDT test laser pulses with center wavelengths within and outside the spectrum of the 25 fs PW laser pulses.   These examples represent LIDT test options which, though they use pulses of much longer duration than the fs PW laser pulses, are nevertheless much more commonly available than are fs pulse LIDT test options. The option of performing LIDT tests with fs PW use lasers themselves is very unlikely because these are large scale laser systems dedicated to non-LIDT-test purposes. Taking them off line and configuring them for LIDT tests would be prohibitively expensive in terms of both time and cost. For fs lasers in general, there are three basic center wavelength options: [1] 1054 nm (or 1030 nm) based on Nd:glass gain media; 910 nm based on optical parametric chirped pulse amplification using KDP, DKDP, or LBO crystals pumped by the frequency doubled output of Nd:glass gain media;[3] and 800 nm based on Ti:Sapphire laser technology. Of these, Ti:Sapphire based lasers are the most available. This leaves limited prospects for obtaining LIDT tests with fs pulses of center wavelengths other than 800 nm, and gives motivation to consider what might be learned about the laser damage characteristics of a BBHR coating by conducting LIDT tests with more readily available lasers having longer, sub-ps, ps, or ns pulses such as depicted in Fig. 1. These longer pulses cause laser damage based on a combination of mechanisms ranging from intrinsic, especially in the sub-ps pulse regimes, to damage in the ns regime controlled by defects from contamination or structural anomalies at the nanoscale level in the coating layers.[4] This mix of damage mechanisms offers some promise that it may be possible to at least gain insight into, if not quantitative estimates of, fs laser damage behaviors from LIDT tests with longer pulses.

While the spectrum of a fs PW pulse spans most if not all of the HR band of an appropriately designed BBHR coating, the bandwidths of 300 fs and 1 ns pulses are in the range, respectively, of 10 nm and < 1 nm, as illustrated in Fig. 1(c). Thus, LIDT tests with 300 fs or 1 ns pulses could probe the laser damage behavior of a BBHR coating in 10 nm or < 1 nm segments of its HR band. To conduct such tests over the entire HR band would, of course, require some way of tuning the center wavelengths of these long-pulse LIDT lasers across the HR band of the BBHR coating. Another option would be to shift the HR band of the BBHR coating with respect to LIDT laser center wavelength. This could be accomplished by changing the AOI for the LIDT tests compared to the use AOI for which the BBHR coating was designed. This could also be accomplished in the case of e-beam deposited BBHR coatings, whose HR bands usually shift due to humidity, by controlling the humidity of an ambient LIDT test environment. Such shifts of the HR band are illustrated in Fig. 1(c), which shows the cases of the BBHR spectrum shifted down or up in wavelength to allow the spectra of LIDT test lasers with center wavelengths offset from λ_0 to overlap the HR band. Such shifted HR bands would expand options for LIDT tests of the BBHR coating within its HR band using available LIDT lasers of pulse lengths matching or longer than that of the fs PW laser, and whose pulse spectra would otherwise completely or partially overlap with wavelengths of high transmission of the un-shifted BBHR transmission spectrum. By way of caution for this latter approach to shifting the HR band, there is evidence that coatings with absorbed water in humid environments exhibit little to no degradation of LIDT compared to in vacuum environments.[6, 7] So, LIDTs measured in humid environments may be overestimates of the corresponding LIDTs under vacuum conditions.

The preceding possibilities raise questions about the validity and usefulness of LIDT tests of a BBHR coating with shifted HR bands and with laser pulses different from the fs PW laser pulses in center wavelength and/or in pulse duration. We address several of these questions. First, do LIDT tests with longer, sub-ps, ps, or ns pulses have value regarding fs pulse laser damage behavior? Yes, they do, because studies have shown that there are trends in LIDTs going from longer, ns pulses down to the fs pulse regime.[4, 8 – 10] Next, do LIDT tests at AOIs different from the use AOI have value? Yes, they do, because E-fields for quarter-wave type HR coatings at wavelengths within the HR band at other AOIs behave similarly to E-fields at the use AOI. This E-field behavior, as described above, is characterized by the intensity peaks that quench into the coating layers,[5] and is favorable to higher LIDTs. Another factor regarding LIDT tests at different AOIs is that, as AOI increases, projected fluence on coating layers decreases as cosine of the AOI, favoring higher LIDT, while optical path in coating layers increases also as cosine of the AOI, favoring lower LIDT. Though these geometrical effects depend on other factors such as how many layers play a strong role in the reflection process, they nevertheless do influence LIDTs in opposite ways as AOI changes, and may reduce differences between LIDTs measured at one AOI compared to those measured at another AOI. A further question is the following. Do LIDTs for HR bands shifted in wavelength from the HR band of the PW use laser have value? Yes, they do, based on the E-field behaviors over HR bands as mentioned above. There is, however, a caution to take into account in comparing LIDTs for shifted HR bands, namely, band-gap related intrinsic laser damage may be higher (lower) for HR bands below (above) the use HR band. Finally, if the use environment is vacuum, do LIDT tests in humid ambient environments have value? Yes, they do, because coatings with absorbed water in humid environments exhibit little to no degradation of LIDT compared to in vacuum (dry) environments.[6, 7] The caution to take into account is, as we mentioned above, that LIDTs measured in humid environments may overestimate what the corresponding LIDTs will be under vacuum conditions.

Coatings for BBHR at 45^o, Ppol of fs pulses with 800 nm - 1000 nm spectra

We explore LIDT test issues of the previous section using a BBHR coating we have designed and deposited by means of ion assisted e-beam evaporation in Sandia's large optics coating chamber[11, 12] for 45^o AOI, Ppol and fs pulse spectra from 800 nm to 1000 nm. The coating consists of TiO_2/SiO_2 layer pairs and its reflectivity performance requirement was that it provide R > 99.5% at 45^o AOI, Ppol over the 800 nm-to-1000 nm band. Figure 2 shows the design transmission spectrum and the measured transmission spectrum of this coating as deposited in Run 072, the coating run that produced the coating for use in a vacuum environment. All of the measured spectra in this study were made using a PerkinElmer Lambda 950 spectrophotometer. In the case of Fig. 2, the spectral measurement was made with the sample compartment of the Lambda 950 under dry (0% RH) conditions, which is the ambient environment that most closely matches the vacuum environment of fs PW use lasers. This transmission spectrum shows that the coating meets the design reflectivity performance requirement quite well, providing R > 99.5% at 45^o AOI, Ppol, over a 213 nm band from 805 nm to 1018 nm.

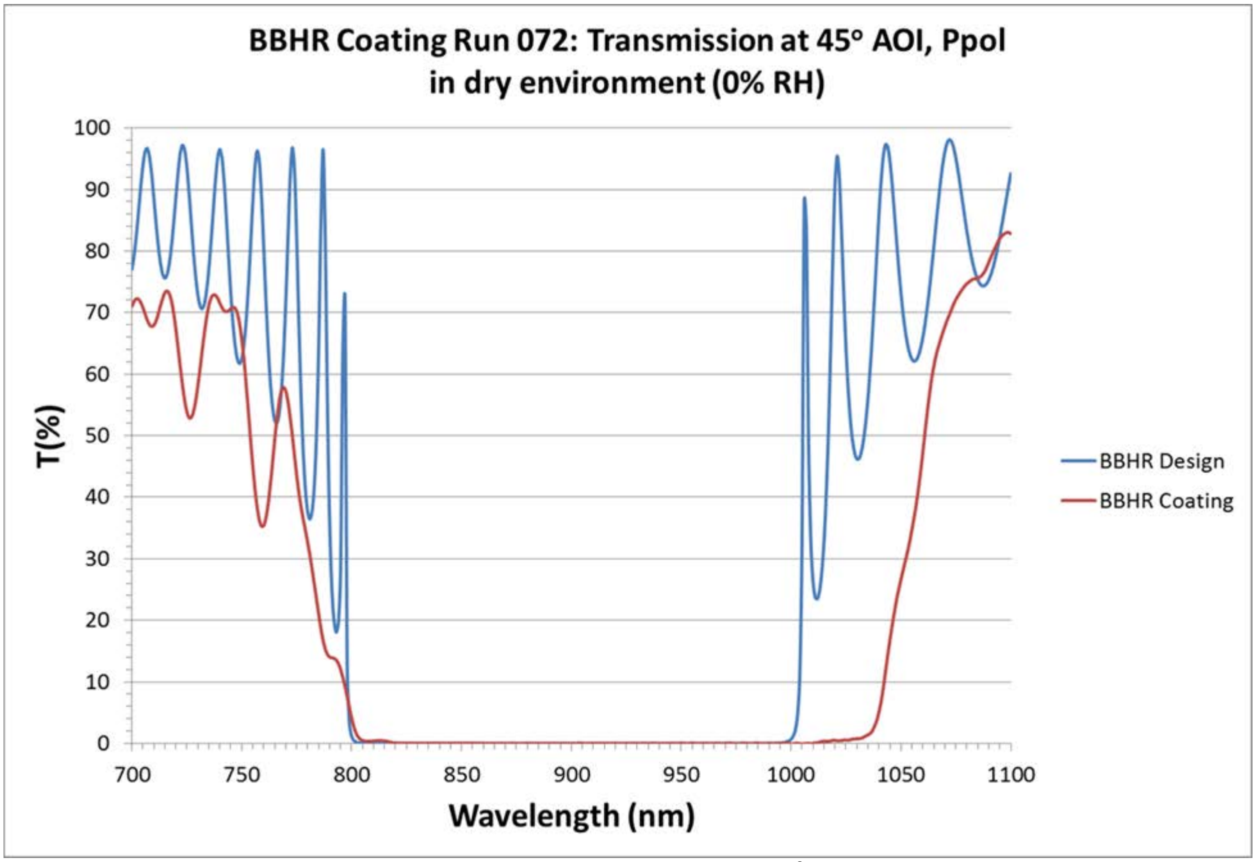
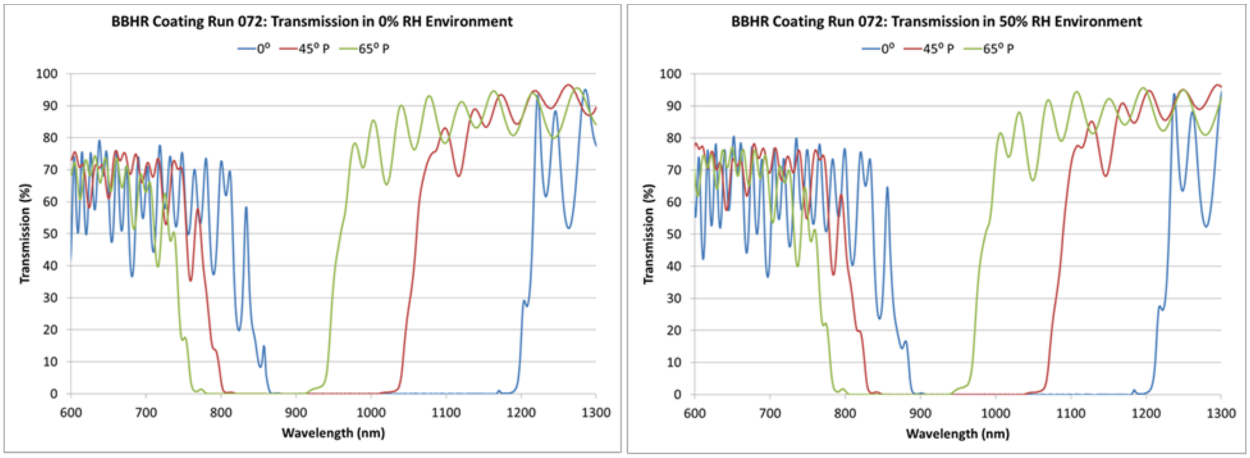


Figure 2: Transmission spectrum as measured under dry (0% RH) conditions at 45^o AOI, Ppol for the BBHR coating of Run 072, with the measured spectrum shown in comparison to the coating's corresponding design transmission spectrum.

Figure 3 shows the measured transmission spectra of this Run 072 coating for 0^o, 45^o, and 65^o AOI at 0% RH and 50% RH conditions in the Lambda 950 sample compartment. The HR band for R > 99.5% is shown below the spectral graphs of Fig. 3 for each measured spectrum. Figure 4 shows a similar set of measured transmission spectra for a BBHR coating of the same design but deposited in a different coating run, Run 071, in which we set the layer thickness calibration factors with a goal of producing a coating that meets the design HR band requirement of R > 99.5% from 800 nm to 1000 nm at 45^o AOI, Ppol under 50% RH conditions. Run 071 was largely successful in achieving this goal as Fig. 4 confirms, with R > 99.5% extending from 799 nm to 987 nm for the coating's 45^o AOI, Ppol transmission spectrum under 50% RH conditions. A trend evident in Figs. 3 and 4 is that the HR band of a BBHR coating decreases as AOI increases.



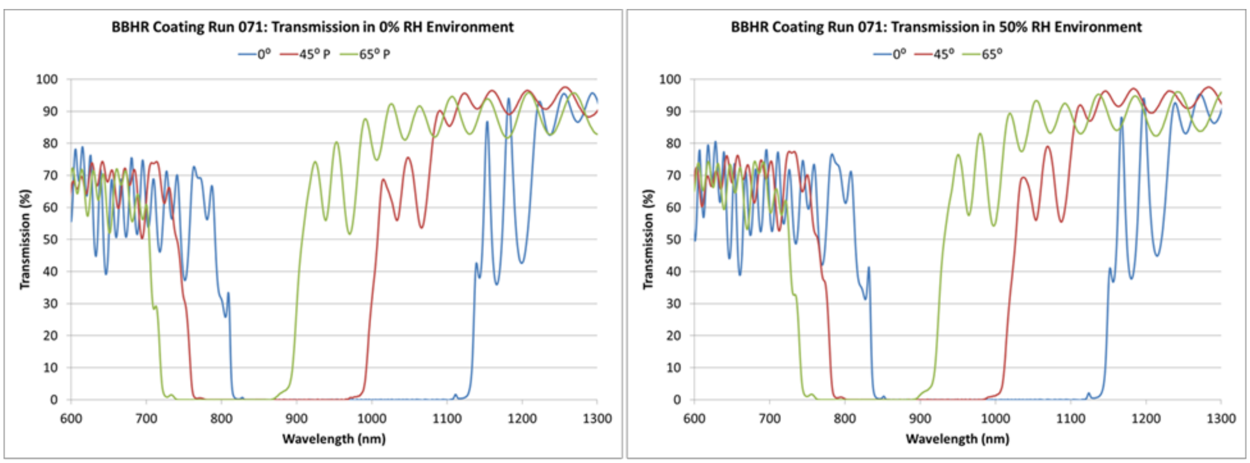
Δλ for R > 99.5% (0% RH)

0°:	303 nm (866 – 1169 nm)
45° P:	213 nm (805 – 1018 nm)
65° P:	137 nm (779 – 916 nm)

Δλ for R > 99.5% (50% RH)

0°:	291 nm (891 – 1182 nm)
45° P:	196 nm (846 – 1042 nm)
65° P:	139 nm (803 – 942 nm)

Figure 3: Measured transmission spectra of the BBHR coating of Run 072 for 0° AOI, and for 45° and 65° AOI, Ppol, at 0% RH and 50% RH ambient conditions. The HR band, Δλ, for R > 99.5% is shown below the graphs for each measured spectrum.



Δλ for R > 99.5% (0% RH)

0°:	289 nm (819 – 1108 nm)
45° P:	196 nm (774 – 970 nm)
65° P:	132 nm (739 – 871 nm)

Δλ for R > 99.5% (50% RH)

0°:	266 nm (854 – 1120 nm)
45° P:	188 nm (799 – 987 nm)
65° P:	133 nm (762 – 895 nm)

Figure 4: Measured transmission spectra of the BBHR coating of Run 071 for 0° AOI, and for 45° and 65° AOI, Ppol, at 0% RH and 50% RH ambient conditions. The HR band, Δλ, for R > 99.5% is shown below the graphs for each measured spectrum.

Figure 5 shows the transmission spectrum of the Run 071 coating at 0% RH, 15% RH, and 50% RH for 45° AOI, Ppol as an example of how the spectrum shifts with respect to RH for a given AOI. The spectra of Figs. 3 - 5 show the range of HR bands available for LIDT tests of the coating under different conditions of ambient humidity and at different AOIs. In practice, shifting the HR band of a coating by setting and maintaining specific ambient humidity levels requires sophisticated monitoring and closed loop feedback control of RH, and is expensive and not easy to achieve. We managed with considerable difficulty to obtain transmission scans with the Lambda 950 spectrophotometer under the 15% and 50% RH conditions by introducing into the sample compartment a combination of dry air and air made humid due to moisture arising from a container of warm water. On the other hand, setting AOI of LIDT tests at specific values is easy to achieve. For this reason, we decided to use AOI as a means of shifting the HR band of our BBHR coatings for LIDT tests under dry (0% RH) or nearly dry conditions.

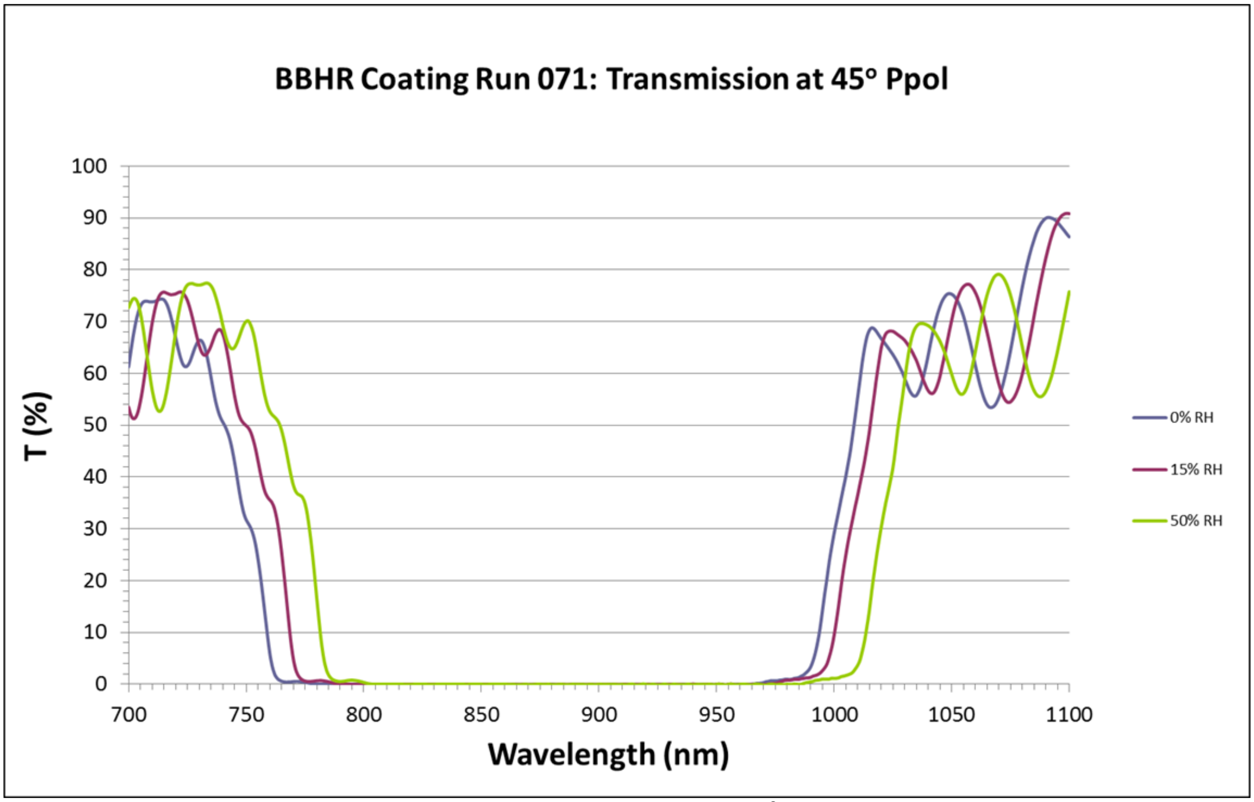


Figure 5: Measured transmission spectra of the BBHR coating of Run 071 at 45^o AOI, Ppol, under 0%, 15% and 50% RH conditions.

LIDT tests of the BBHR coating of Run 072

LIDT tests of the BBHR coating of Run 072 were performed by CEA-CESTA in France using the laser test facility called DERIC[13] with 675 fs pulses of 1053 nm center wavelength for 1-on-1 and 10-on-1 tests based on ISO 11254-1[14] and ISO 11254-2[15] protocols, respectively. The test environment was enclosed and maintained nearly dry, at ~ 10% RH. The LIDT tests were at normal incidence (0^o AOI) in order to probe the coating in the central part of its HR band, and at 40^o AOI, Ppol, in order to probe the coating near the long wavelength edge of its HR band. Figure 6 shows where the LIDT test laser center wavelength, 1053 nm, is located within the HR bands for 0^o AOI and 40^o AOI, Ppol. The E-field plots of Fig. 6 for our BBHR coating design are examples of how the E-field intensity peaks quench less rapidly into coating layers at wavelengths near the edge of the HR band than they do within its central spectral zone. We are interested in comparisons between LIDT behaviors at wavelengths well within the HR band, between the central zone and edge of the HR band, and near the HR band edge. LIDT differences between these situations may be associated with corresponding differences of the E-field behaviors in the coating, as described in previous paragraphs.

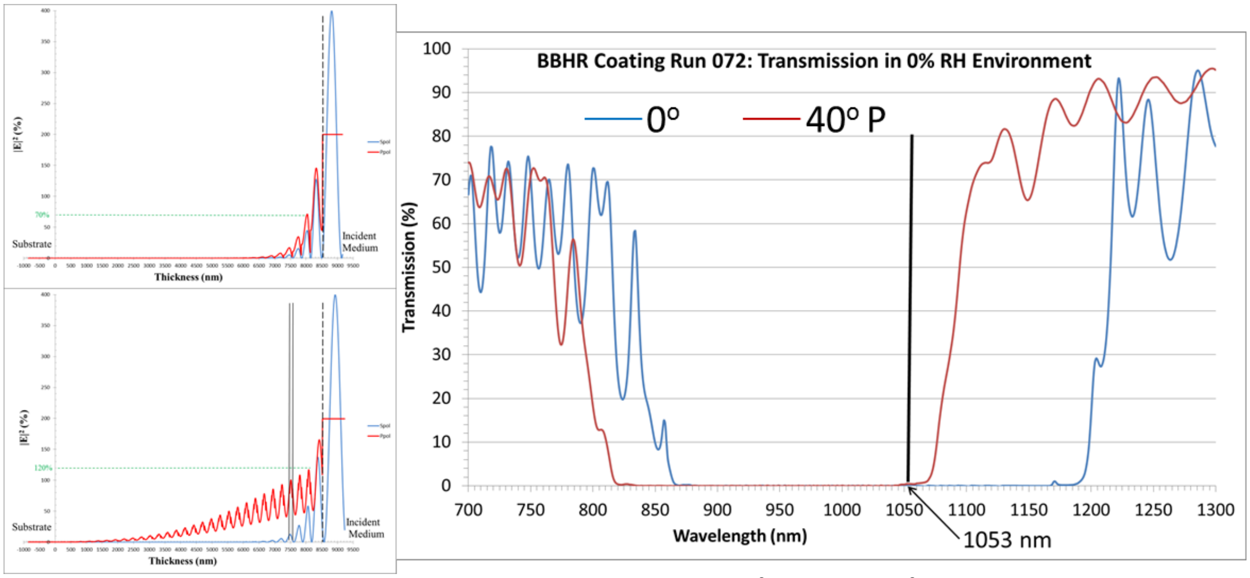


Figure 6: Measured transmission spectra of the BBHR coating of Run 072 at 0° AOI and at 40° AOI, Ppol under dry (0% RH) conditions (right-hand graph). The thick black vertical line indicates 1053 nm, the center wavelength of the CEA-CESTA 675 fs LIDT test laser pulses. The left-hand graphs show E-field intensities in the coating layers for 45° AOI, Ppol (in red) and Spol (in blue), for the BBHR coating design at a wavelength well within the central zone of the HR band (top graph) and at the HR band edge (bottom graph). The black dashed vertical lines indicate the boundary of the coating with the incident medium.

Figure 7 shows plots of damage probability versus laser fluence for the CEA-CESTA 1-on-1 and 10-on-1 LIDT tests at the 0° and 40° AOIs. In all cases, the transition of the damage probability from 1 to 0 is very sharp, indicating that the damage is primarily intrinsic and not governed by defects in the coating. This, in fact, is what we would expect for laser damage caused by these 675 fs pulses. The respective 1-on-1 and 10-on-1 LIDTs are higher for 0° AOI than for 40° AOI. This is counter-intuitive considering that the lower projected fluence on the coating at 40° AOI than at 0° AOI would favor higher LIDT at 40° AOI than at 0° AOI. We conclude that these results are related to the differences in E-field behaviors between the central and edge spectral zones of the HR band, examples of which are shown in Fig. 6. The decrease of LIDT between the 1-on-1 and 10-on-1 tests is ~ 14% (from 1.34 J/cm^2 to 1.15 J/cm^2) for 0° AOI (i.e., at wavelengths in the central part of the HR band) while it is larger, ~ 30% (from ~ 1.15 J/cm^2 to ~ 0.8 J/cm^2), for 40° AOI (i.e., at wavelengths near the edge of the HR band). It happens for these tests that the decrease between LIDTs at wavelengths in the central part of the HR band and near the edge of the HR band is also ~ 14% (from 1.34 J/cm^2 to 1.15 J/cm^2) for 1-on-1 tests and ~ 30% (from 1.15 J/cm^2 to 0.8 J/cm^2) for 10-on-1 tests. We also attribute these 1-on-1, 10-on-1, and HR band center/edge differences in LIDTs to the differences mentioned above between E-field behaviors for wavelengths at the HR band center and edge spectral zones. Overall, we find these LIDT results for 675 fs laser pulses at 1053 nm to be encouraging.

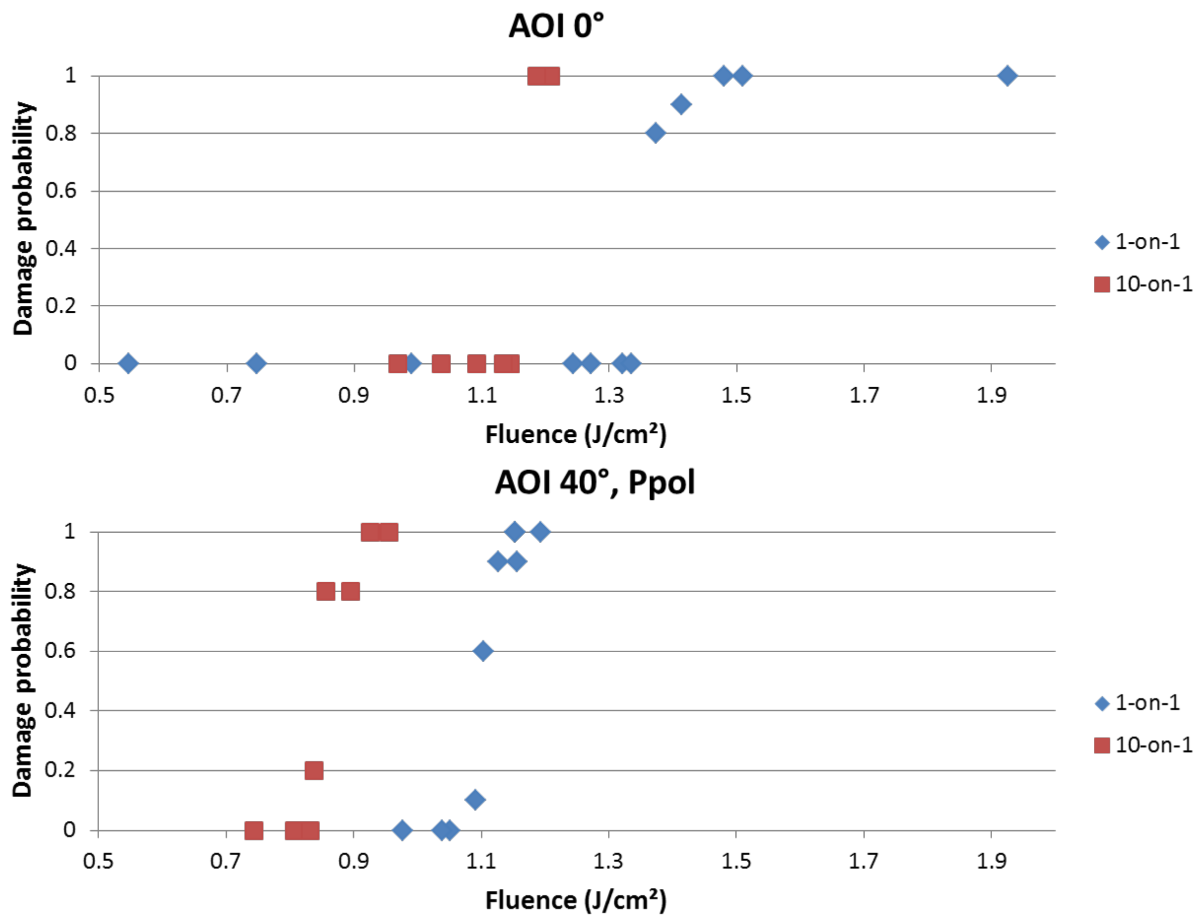


Figure 7: Damage probability versus fluence for 1-on-1 and 10-on-1 LIDT tests of the BBHR coating of Run 072, as measured by CEA-CESTA at 0^o AOI and 40^o AOI, Ppol with 675 fs laser pulses of 1053 nm center wavelength.

LIDT tests of the BBHR coating of Run 071

LIDT tests of the BBHR coating of Run 071 were performed by Spica Technologies, Inc.[16] using the NIF-MEL protocol[17] with 800 ps (~ 1 ns) and 8 ps pulses of 1064 nm center wavelength. The test environment was enclosed and maintained at 0% RH by means of a nitrogen purge. The tests were at 0^o AOI and at 19^o AOI, Ppol. Figure 8 shows where the LIDT test laser center wavelength, 1064 nm, for the NIF-MEL tests is located within the HR bands of the Run 071 coating at 0^o AOI and at 19^o AOI, Ppol. The E-field plots of Fig. 8 are the same as those of Fig. 6 and serve as examples of how the E-field intensity peaks quench less rapidly into coating layers at wavelengths near the edge of the HR band than they do within its central spectral zone. In the case of the 19^o AOI, Ppol, NIF-MEL LIDT tests, the LIDT laser probes near the coating's HR band edge (see Fig. 8), similar to how the 40^o AOI, Ppol LIDT tests probed the Run 072 BBHR coating (see Fig. 6). The situation is, however, different for the NIF-MEL LIDT tests at 0^o AOI as compared to the 0^o AOI LIDT tests of the Run 072 coating. In the latter tests, the laser probed the coating well within the central zone of its HR band (see Fig. 6) while, in the 0^o AOI NIF-MEL tests of the Run 071 coating, the laser probed the coating in a spectral zone of the HR band between its central and edge zones (see Fig. 8).

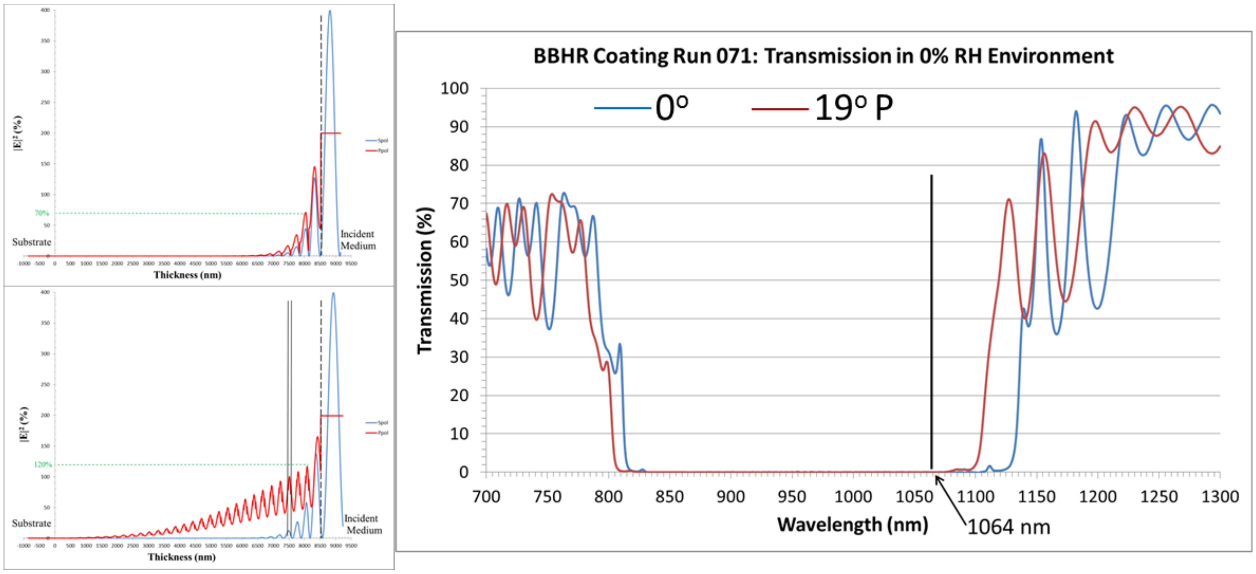


Figure 8: Measured transmission spectra of the BBHR coating of Run 071 at 0° AOI and at 19° AOI, Ppol under dry (0% RH) conditions. The thick black vertical line indicates 1064 nm, the center wavelength of the NIF-MEL 800 ps and 8 ps LIDT test laser pulses. The left-hand graphs show E-field intensities in the coating layers for 45° AOI, Ppol (in red) and Spol (in blue), for the BBHR coating design at a wavelength well within the central zone of the HR band (top graph) and at the HR band edge (bottom graph). The black dashed vertical lines indicate the boundary of the coating with the incident medium.

The 8 ps and 800 ps pulses of these LIDT tests were multi-longitudinal mode with focal spot diameters on the coating surface of 23 μm and 82 μm, respectively. In the NIF-MEL procedure, there is a dense raster scan of the focused laser beam, focal spot by focal spot, over an area of 1 cm x 1 cm of the coating starting at low fluence and continuing at increased fluence levels, with 1 laser shot per focal spot site at each fluence level. Adjacent focal spots overlap each other at 90% of their peak intensities. A camera detects damage, site by site, both damage that is non-propagating (i.e., that occurs but does not grow) as well as propagating (i.e., that occurs in a catastrophic way) and LIDT is determined either by the fluence at which the accumulated number of non-propagating damage sites exceeds 1% of the total number of raster scan sites, or by the fluence at which propagating damage occurs at one or more sites, whichever is the lower fluence. Non-propagating damage is usually related to coating defects that serve as initiation sites for damage mechanisms that occur on ~ ns time scales, while propagating damage often results from intrinsic damage mechanisms based on direct interaction of the laser radiation with the coating layer materials.

Figure 9 shows the NIF-MEL LIDT results in the form of a plot of cumulative number of non-propagating damage sites versus fluence. As can be seen, all LIDTs of Fig. 9 are due to propagating damage, which likely indicates that intrinsic damage occurs at fluence levels lower than those that would lead to LIDTs determined by defect related, non-propagating damage sites over 1% of the raster scan sites. For the tests with 800 ps pulses, the LIDT at 0° AOI (at a spectral zone between the HR band's central and edge zones) is 11 J/cm^2, and is higher than the 9 J/cm^2 LIDT at 19° AOI (at wavelengths near the HR band edge). Also, the cumulative number of non-propagating damage sites is 15 for the tests at 19° AOI compared to 6 for the tests at 0° AOI. This is consistent with the optical field behaviors discussed above and shown in Fig. 8, which have higher peak intensities deeper into the coating layers and consequently sample more layer defects at wavelengths closer to the edge of the HR band than to its central spectral zone. It is not surprising that we see some non-propagating damage with the 800 ps pulses because this pulse duration is in the ~ ns range of time scales for defect-related mechanisms of non-propagating damage. For the tests with 8 ps pulses, no non-propagating damage occurs, indicating that laser damage is primarily intrinsic and not governed by defect-related mechanisms, which is what we expect for the shorter, 8 ps pulses as compared to the longer, 800 ps (~ 1 ns) pulses. Unlike the case of 800 ps pulses, the 8 ps pulse LIDT of 1.25 J/cm^2 for 0° AOI (at a spectral zone between the HR band's central and edge zones) is similar to, but a bit lower than the 1.5 J/cm^2 LIDT for 19° AOI (near the HR band edge). This is, however, consistent with the intrinsic nature of the 8 ps pulse laser damage. The 800 ps and 8 ps LIDTs of Fig. 9 scale quite well with (pulse duration)$^{-1/2}$, which is a well-known LIDT scaling law for this range of pulse durations.[8] Also, the NIF-MEL LIDTs for 8 ps pulses at 1064 nm (see Fig. 9) are about the same as or a bit higher than the ISO 11254-1 LIDTs for 675 fs pulses at 1053 nm (see Fig. 7), and are consistent, both in magnitude and in pulse-duration trend, with LIDTs of TiO_2 films for pulses of 800 nm center wavelength.[10] This close similarity of LIDT values and pulse-duration trends indicate that the results of Figs. 7 and 9 provide a reasonable characterization of the laser damage behavior of the BBHR coatings.

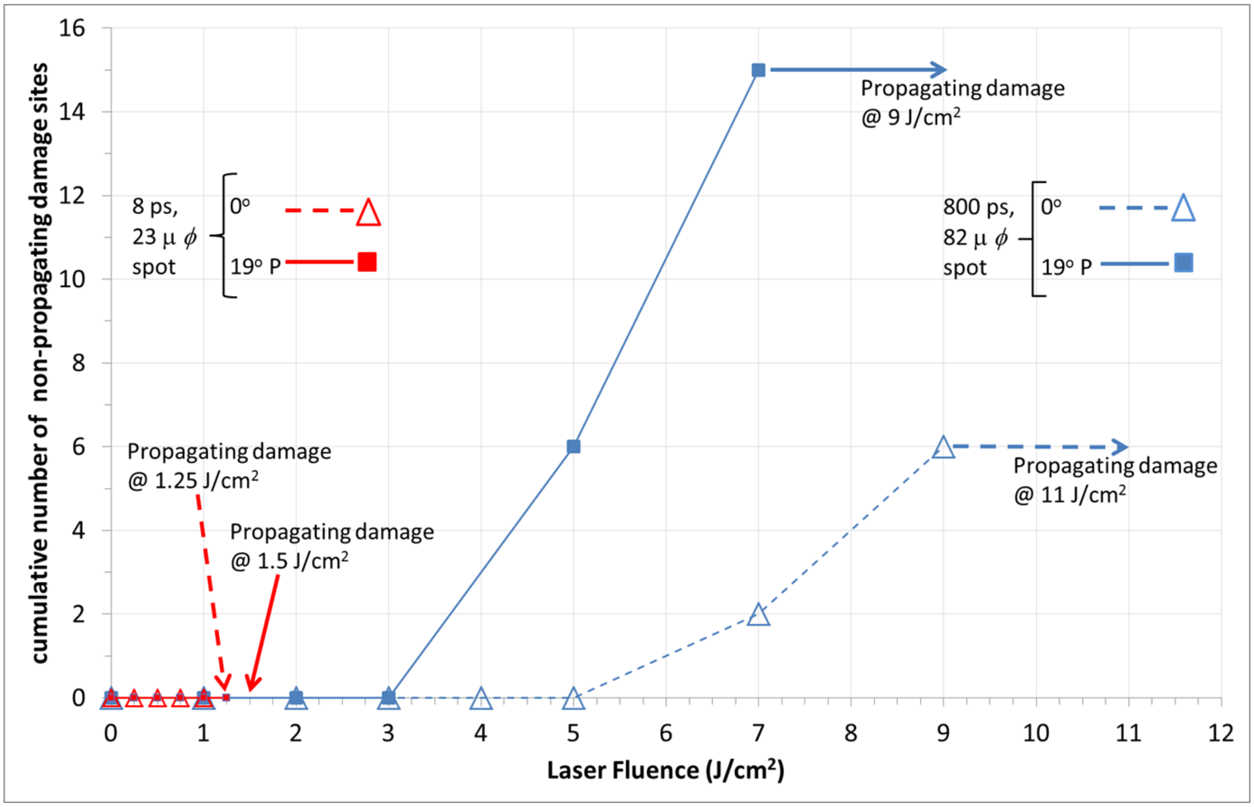


Figure 9: Cumulative number of non-propagating laser-induced damage sites versus laser fluence for NIF-MEL LIDT tests of the BBHR coating of Run 071 with 800 ps and 8 ps laser pulses of 1064 nm center wavelength at 0° AOI and at 19° AOI, Ppol. The arrows point to the fluences at which propagating laser-induced damage occurred.

Summary and a Proposal

We have highlighted dilemmas in LIDT testing of BBHR coatings arising from differences between LIDT test lasers and test environments compared to fs PW use lasers and their vacuum environment. We then argue the value of LIDT tests of BBHR coatings using available fs – to – ns laser pulses with AOI and RH shifts of HR bands of BBHR coatings to make the HR bands match the spectra of the LIDT test laser pulses. LIDT tests of a coating designed and produced by us to provide a 200 nm HR band centered at 900 nm for reflection of fs PW laser pulses at 45° AOI, Ppol serve as examples of our suggested approach of using available LIDT test lasers to gain insight into laser damage characteristics of BBHR coatings. These tests were under dry conditions with HR bands shifted by means of AOI tuning, and used a 675 fs, 1053 nm laser, and 8 ps and 800 ps, 1064 nm lasers. Tuning of the AOI for the BBHR coating allowed our LIDT tests to probe laser damage behaviors at wavelengths within the central zone of the HR band, near the HR band edge, and between these two spectral zones of the HR band. We emphasize that these LIDT tests have value in providing comparisons of laser damage behaviors for different spectral zones of the HR band and in confirming pulse scaling trends from the ns to 675 fs pulse regimes, but allow only speculative, relative estimation of LIDTs for pulse durations in the few tens of fs regime. Further LIDT tests would be necessary before we would even speculate on values for fs LIDTs of our BBHR coatings. To this end, we propose the use of a laser with 350 fs pulses, whose center wavelength is tunable by means of optical parametric amplification, in order to conduct 45° AOI, Ppol LIDT tests in vacuum of our BBHR coating in ~ 10 nm band intervals from 800 nm to 1000 nm.

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