SAND2009-8285C

Meeting thin film design and production challenges for laser damage resistant optical coatings at the Sandia Large Optics Coating Operation

John Bellum[*,#], Damon Kletecka[*], Patrick Rambo, Ian Smith, Mark Kimmel, Jens Schwarz, Matthias Geissel, Guild Copeland, Briggs Atherton
Sandia National Laboratories, PO Box 5800, MS 1193, Albuquerque, NM 87185

Douglas Smith, Claire Smith
Plymouth Grating Laboratory, 5 Commerce Way, Carver, MA 02330,

Constantine Khripin
University of New Mexico, Advanced Materials Laboratory
1001 University Blvd. SE, Suite 100, Albuquerque, NM 87106

ABSTRACT

Sandia's Large Optics Coating Operation provides laser damage resistant optical coatings on meter-class optics required for the ZBacklighter Terawatt and Petawatt lasers. Deposition is by electron beam evaporation in a 2.3 m x 2.3 m x 1.8 m temperature controlled vacuum chamber. Ion assisted deposition (IAD) is optional. Coating types range from anti-reflection (AR) to high reflection (HR) at S and P polarizations for angle of incidence (AOI) from 0^o to 47^o.

This paper reports progress in meeting challenges in design and deposition of these high laser induced damage threshold (LIDT) coatings. Numerous LIDT tests (NIF-MEL protocol, 3.5 ns laser pulses at 1064 nm and 532 nm) on the coatings confirm that they are robust against laser damage. Typical LIDTs are: at 1064 nm, 45^o AOI, Ppol, 79 J/cm^2 (IAD 32 layer HR coating) and 73 J/cm^2 (non-IAD 32 layer HR coating); at 1064 nm, 32^o AOI, 82 J/cm^2 (Ppol) and 55 J/cm^2 (Spol) (non-IAD 32 layer HR coating); and at 532 nm, Ppol, 16 J/cm^2 (25^o AOI) and 19 J/cm^2 (45^o AOI) (IAD 50 layer HR coating). The demands of meeting challenging spectral, AOI and LIDT performances are highlighted by an HR coating required to provide R > 99.6% reflectivity in Ppol and Spol over AOIs from 24^o to 47^o within ~ 1% bandwidth at both 527 nm and 1054 nm.

Another issue is coating surface roughness. For IAD of HR coatings, elevating the chamber temperature to ~ 120 ^{o}C and turning the ion beam off during the pause in deposition between layers reduce the coating surface roughness compared to runs at lower temperatures with the ion beam on continuously. Atomic force microscopy and optical profilometry confirm the reduced surface roughness for these IAD coatings, and tests show that their LIDTs remain high.

Keywords: laser induced damage threshold, large optics coatings, ion-assisted deposition, coating surface roughness, anti-reflection and high reflection optical coatings, reflectivity, diffuse reflectivity, high intensity pulsed lasers

* JB and DK are contract associates to Sandia National Laboratories. JB is with Sandia Staffing Alliance, LLC and DK is with LMATA Government Services, LLC.

jcbellu@sandia.gov ; phone: 505-845-7559

1. INTRODUCTION: SANDIA'S ZBACKLIGHTER LASERS AND LARGE OPTICS COATING OPERATION

The ZBacklighter Laser Facility, as part of Sandia's Pulsed Power Sciences program (http://www.sandia.gov/pulsedpower/), provides x-ray backlighting diagnostics on an almost daily basis for the Z Accelerator magnetic pinch [1]. There are two basic ZBacklighter lasers, ZBeamlet [2] and ZPetawatt.[3] They can each generate x-ray bursts energetic enough to penetrate the high energy density core of the Z pinch when their kilo joule class short pulse, high peak power beams come to focus on foils near the axis of the pinch. Both ZBeamlet and ZPetawatt lasers rely on power amplification in neodymium-glass amplifier slabs of ns class laser pulses at 1054 nm, the wavelength of the fundamental (1ω) laser frequency. ZBeamlet converts these amplified 1ω pulses by means of frequency doubling to the second harmonic (2ω) at 527 nm. Its pulses are of duration in the range 0.3 – 8 ns, but the most common operation is with 1 – 2 ns pulses with pulse energies that can reach up to ~ 2 kJ at 527 nm. The ZPetawatt laser, on the other hand, uses pulse stretching before and pulse compression after the power amplification stage to produce intense output pulses at the 1ω wavelength. The output pulse durations can range down to ~ 500 fs and the output pulse energies can extend up to ~ 420 J in the current configuration with the prospect of future upgrades increasing this to ~ 1 kJ.

Sandia established the Large Optics Coating Operation to provide high laser induced damage threshold (LIDT) optical thin film coatings for the large optics of the ZBacklighter laser beam trains. The large dimensions of the optics, from tens of cm up to and exceeding 1 m, as well as the high LIDTs of their coatings are essential to the effective handling of the levels of peak laser intensities produced by the ZBacklighter lasers. By being large in dimension, the optics allow for expansion of the laser beams to larger cross sectional areas over which the high intensity laser light can be distributed at correspondingly reduced fluence levels. But ultimately the allowed levels of such reduced fluences are determined by the LIDT of the optics themselves and their coatings. The expanded ZBeamlet laser beam can present 2.5 – 10 J/cm^2 in a 1 ns pulse of 527 nm light over its cross section. In the case of the ZPetawatt laser, the beam can present 2.5 – 4 J/cm^2 in a 700 fs pulse of 1054 nm light over its cross section. Our goal in large optics coatings is that their LIDTs exceed these fluences, and preferably by factors of ~ 2 in order to handle hot spots in the beams.

The large optics coating chamber at Sandia is 2.3 m x 2.3 m x 1.8 m in size and opens to a Class 100 clean room equipped for handling, cleaning and preparing large optics for coating. Deposition of the thin film optical coatings is by conventional electron beam (e-beam) evaporation provided by 3 e-beam sources in the chamber. Ion assisted deposition (IAD) is available as an option in which ions from an ion source enhance or alter the deposition of the e-beam evaporated coating molecules. The optical substrates are held in fixtures that undergo planetary rotation near the top of the vacuum chamber. In the 3-planet option, each planet fixture can hold optical substrates up to 94 cm in diameter. In a counter-rotating, 2-planet option for future use, each planet fixture can hold substrates up to 1.2 m in one dimension and 80 cm in the other. Achieving coatings of high LIDT depends not only on judicious choice of coating materials but also on how the substrate surfaces are prepared for coating and how the coatings are deposited. Sandia's operation employs hafnia and silica as the high and low index thin film materials, respectively, since coatings of these materials are known for resistance to laser damage [4]. Hafnia layers are deposited by e-beam evaporation of hafnium metal in the presence of oxygen at a back pressure of ~ 10^{-4} Torr whereas silica layers are deposited by direct e-beam evaporation of silica. One of the ZBacklighter large optics, the anti-reflection (AR) coated debris shield, protects optics from Z pinch debris and as a result suffers damage that renders it unusable for future shots. Maintaining an adequate inventory of debris shields is thus a primary large optics coating mission at Sandia.

This paper features LIDTs with 3.5 ns laser pulses incident on a wide range of AR and high reflection (HR) coatings produced by Sandia's large optics coater. This is in the pulse regime of the ZBeamlet laser and of the power amplification stage of the ZPetawatt laser. The tests, performed by Spica Technologies Inc. (http://www.spicatech.com/), show excellent laser damage resistance of the coatings in this ns laser pulse regime in all cases. We have also performed in-house LIDT tests with 400 fs laser pulses at 1054 nm, in the output pulse regime of the ZPetawatt laser, and report on them elsewhere in these proceedings [5].

Though obtaining high LIDT coatings is critical for the ZBacklighter lasers, other issues such as coating stress and coating surface roughness are also important [4]. We address these issues in the context of IAD HR coatings on fused silica substrates in vacuum, as is common and often necessary for lasers of the ZBacklighter class. In our coating processes, these IAD HR coatings tend to have higher surface roughness than their non-IAD counterparts. Such surface roughness leads to diffuse reflection that detracts from the specular reflection the HR coatings could otherwise provide. We report on an investigation into how the surface roughness of our IAD HR coatings depends on the temperature in the coating chamber during deposition and on whether the ion beam is kept on or off during the pause in deposition between layers. The paper includes results of atomic force microscopy (AFM) and optical profilometry measurements comparing the differing levels of surface roughness of these coatings, and measurements that show how their reflectivities and LIDTs depend on surface roughness.

Finally, we present the demanding performance requirements, in reflectivity, wavelength, polarization and LIDT, of a key ZBacklighter mirror, the Petawatt Final Optics Assembly (PW FOA) steering mirror. We developed a 50 layer HR coating design that meets these requirements, and successfully deposited this 50 layer coating on the 75 cm diameter mirror substrate using IAD. The paper includes LIDT results and measured and calculated spectra showing the coating, as deposited, meets the mirror's performance requirements. A conclusion summarizes the important results of this work.

2. LASER INDUCED DAMAGE THRESHOLDS FOR SANDIA COATINGS

Our LIDT tests follow the NIF-MEL protocol which involves raster scans of a multimode Nd:YAG laser beam spot over a grid of ~ 2500 sites in a 1cm x 1cm area. We had tests done at the fundamental Nd:YAG wavelength of 1064 nm (close to the 1ω ZBacklighter wavelength) as well as at the frequency doubled wavelength of 532 nm (close to the 2ω ZBacklighter wavelength). The laser operated at a 5 Hz repetition rate with 3.5 ns pulse duration. In the raster scan, the laser spot overlaps itself from one grid site to the next at its 90% peak intensity radius. In our tests, the laser fluence in the cross section of the laser beam started at 1 J/cm^2 for the first raster scan and increased in increments of 3 J/cm^2 for each successive scan. Among laser damage test methods [4], this constitutes a type of N:N procedure over a 1 cm^2 area in raster scan iterations with the fluence increasing iteration to iteration. At each fluence level, the test monitors the number of new laser induced damage sites, distinguishing between those that form without growing in size and those that form and continue growing in size. We refer to damage sites that form without further growth in size as non-propagating (NP) damage, and those that form and continue growing in size as propagating (P) damage. We assess the LIDT as the lowest between two fluence thresholds, the Fail P threshold for which at least one propagating damage site occurs, or the Fail NP threshold for which the number of non-propagating damage sites accumulates to at least 25, corresponding to NP damage over ~ 1% of the 1 cm^2 scan area (~ 1% of the ~ 2500 scan sites). These are fluences in the beam cross section, and correspond to actual fluences on the coated optical surface only for normal incidence of the beam to the surface. At non-normal angle of incidence (AOI), the fluence on the coated surface is less than that in the beam cross section by a factor of the cosine of the AOI. All LIDTs that we report refer to fluences in the cross section of the laser beam.

Both the Fail P and the Fail NP thresholds are important and together indicate the damage behavior we can realistically expect of the coating when it is in the laser beam train exposed daily to ZBacklighter laser shots. The Fail P threshold lets us know the fluences at which we can avoid catastrophic coating failure resulting from one or more propagating damage sites. The Fail NP threshold lets us know the fluences at which we can keep the area coverage of NP damage to the coating at ~ 1% or less. This 1% gauge of the Fail NP threshold is based on an estimate of when NP damage becomes unacceptable. As the area coverage of NP damage increases to the 1% level, one can expect based solely on geometry that the optical losses due to scattering of light by NP damage sites become appreciable compared to 1% of the laser beam intensity. This approaches a level of loss that we try hard to avoid. For example, by means of AR coatings on transmissive optics we try to keep surface reflection losses below 0.5%. So, the Fail NP threshold is indeed a reasonable gauge for assessing the laser fluence beyond which the degradation of a coating's optical performance due to NP damage is no longer acceptable.

We first present LIDT results for AR coatings which, as we just mentioned, play a vital role in minimizing reflection losses at the surfaces of transmissive optics. These AR coatings consist of 4 layers deposited by the conventional (non-IAD) e-beam process at 200 ^{o}C chamber temperature. They are typically on fused silica, the substrate for ZBacklighter transmissive optics such as lenses and windows as well as the above mentioned debris shields. The lenses and windows are at normal or near normal incidence to the laser beam and often serve as vacuum barriers with the coating in vacuum on one side of the optic and at ambient pressure on the other side. The debris shield is entirely in vacuum. Figure 1 shows the cumulative number of NP damage sites versus laser fluence from LIDT tests on 8 AR coatings at 1064 nm, normal incidence. The six coatings indicated by 1ωAR7 in the legend are for AR at 1054 nm for lenses in the power

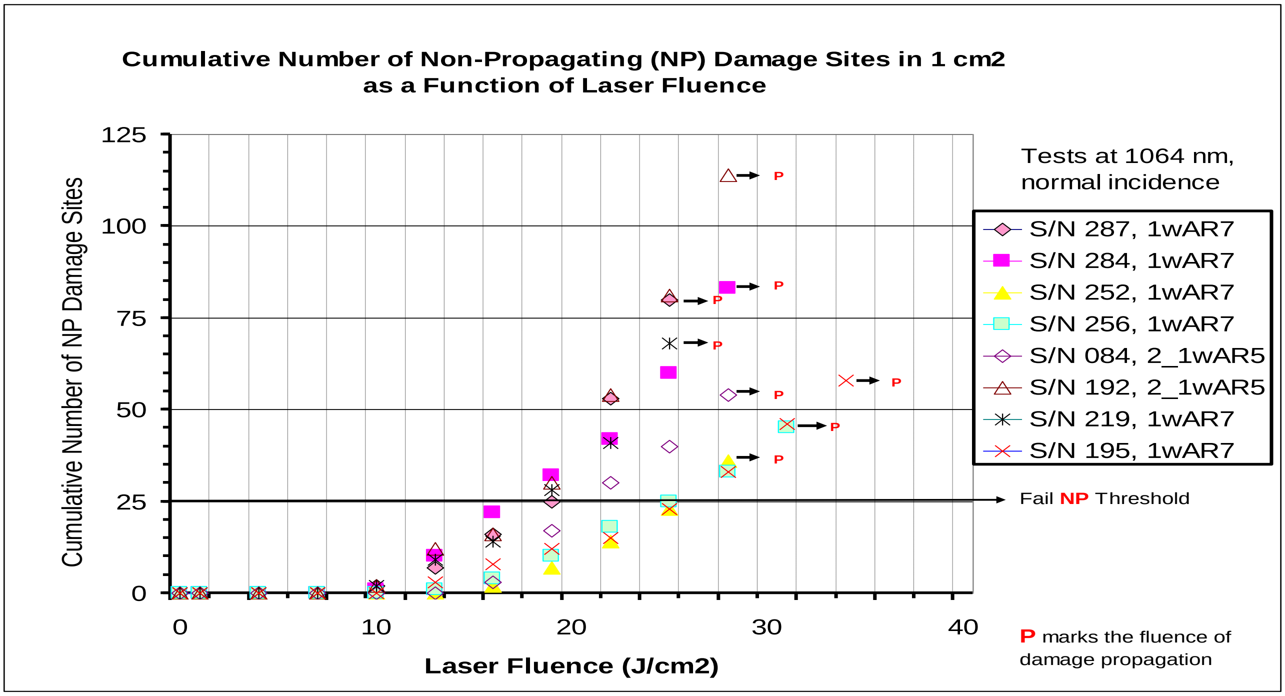


Figure 1. LIDT test results for 8 non-IAD AR coatings deposited on fused silica with the chamber at 200 ^oC.

amplification stages of the ZBacklighter lasers. The two coatings indicated by 2_1ωAR5 are dual wavelength debris shield coatings for AR at 527 nm (2ω) and 1054 nm (1ω), but tested here only for their 1ω LIDT. Debris shields need the dual wavelength AR coatings because the laser beam consists of both the 2ω ZBeamlet working wavelength at 527 nm and also a component at 1054 nm as a result of less than 100% efficient frequency doubling.

A horizontal arrow labeled Fail NP Threshold in Fig. 1 highlights the criterion of 25 cumulative NP damage sites that specifies the Fail NP thresholds which, as seen from the graph, range between ~ 18 J/cm^2 and ~ 27 J/cm^2. The Fail P thresholds, indicated by corresponding letters "P" on the graph, range between ~ 28 J/cm^2 and ~ 37 J/cm^2. For each coating, the Fail NP threshold is lower than the Fail P threshold and thus specifies the LIDT. This is in general the case for our AR coatings. These LIDT values, from ~ 18 J/cm^2 to ~ 27 J/cm^2, exceed the fluences of the ns class pulses of the 1ω ZBacklighter laser beam by a factor of ~ 2 or more, which is a good margin for accommodating fluence hot spots in the beams. It is interesting that the accumulated number of NP damage sites just prior to the occurrence of propagating damage varies considerably (between ~ 35 and ~ 115) among coatings and does not correlate with the Fail P thresholds.

We turn next to HR coatings. Figure 2 presents results of 8 LIDT tests on 6 representative HR coatings from product runs on BK7 mirror substrates using non-IAD E-beam deposition at 200^o C chamber temperature. This is the coating process we use for deposition on BK7. The coatings are all quarter-wave stacks for HR at 1054 nm with differing numbers of layers depending on desired HR performance, and are variously for 32^o and 45^o AOIs. The legend of Fig. 2 lists the polarization (Ppol or Spol) of each test as well as the product mirrors that were coated. The 100 TW mirrors, M6', M4' and M4, are all 30 cm in diameter and are in an optional 100 TW beam train that folds off from the ZPetawatt beam train. The PW fold mirrors, M7' and M8', are 94 cm diameter substrates truncated to a height of 60 cm. LIDT Tests 1 and 2 were at 32^o AOI, Ppol on identical 32 layer HR coatings from different coating runs; Test 3 was at 45^o AOI, Spol on a 24 layer HR coating; Test 4 was at 45^o AOI, Ppol on an 18 layer HR coating; Tests 5 and 6 were at 45^o AOI, Ppol and Spol, respectively, on the same 32 layer HR coating; and Tests 7 and 8 were like Tests 5 and 6, and on their same coating, but from a different coating run. Figure 2 is in the same format as Fig. 1, including the horizontal Fail NP Threshold arrow. The LIDTs range from a low of ~ 70 J/cm^2 to a high of ~ 91 J/cm^2. In the case of Test 5, no damage occurred at all out to 88 J/cm^2, which was the fluence limit for that test. In all but one case, the LIDT is specified by the Fail P threshold. This is in marked contrast to the AR coatings of Fig. 1 for which the LIDT is specified by the Fail NP threshold in all cases. These results indicate that NP damage, especially leading to damage failure, is unlikely to occur in HR coatings such as these. The coating of Test 2 is interesting. It was deposited in two separate runs. We had to stop the first run in the 27th layer due to a failed E-beam emitter, so decided to see how robust the coating might be if we completed it out to 32 layers in a 2nd run. The final, dual-run coating, though not usable due to considerable crazing, exhibited at 70 J/cm^2 a decent LIDT even if it was the lowest of our tests. Another interesting result is the comparison between Spol and Ppol LIDTs. One is not consistently larger than the other. In Spol and Ppol tests on the same coating (Tests 5 and 6, and Tests 7 and 8), we find (88 J/cm^2 Spol) vs. (> 88 J/cm^2 Ppol) in one case, and (82 J/cm^2 Spol) versus (73 J/cm^2 Ppol) in the other case. Our highest and lowest LIDT values were at Ppol while our Spol LIDT values were high with less variation. All of these LIDTs exceed the fluence levels of the ZBacklighter laser 1ω ns class pulses by factors > 7.

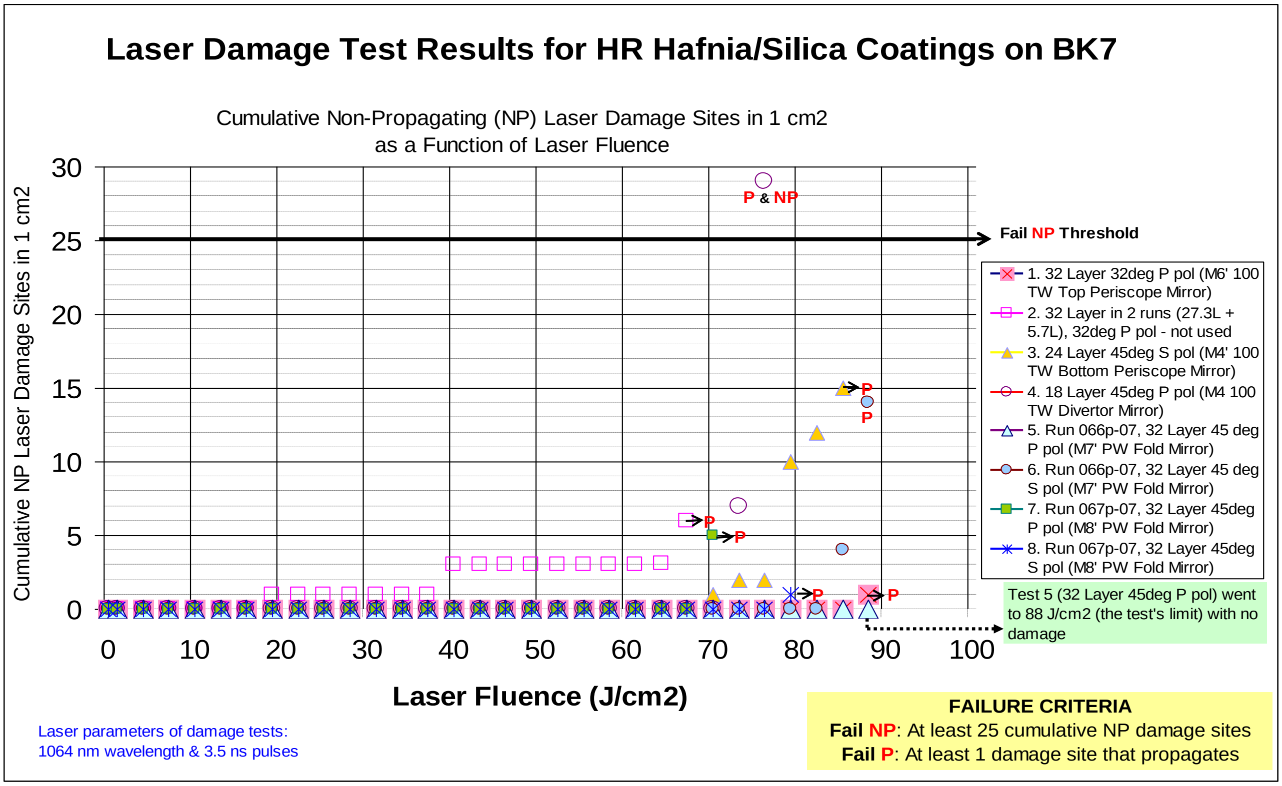


Figure 2. LIDT test results for 8 non-IAD HR coatings deposited on BK7 with the chamber at 200 °C.

Figure 3 features LIDT tests at 1064 nm on 6 HR coatings, of which 5 are IAD and one is non-IAD for comparison with its IAD counterparts. We use the IAD coating process for HR coatings on fused silica substrates intended for use in vacuum. The ion bombardment provided by IAD in conjunction with the deposition of coating molecules at the surface of the substrate leads to denser coatings of less stress mismatch with the substrate.[4] Such coatings are not as likely to delaminate from the substrate in vacuum environments. Our IAD coatings of Fig. 3 are from runs at a 70 °C chamber temperature with the ion beam on continuously. LIDT Tests 1 – 4 as listed in the legend are on identical 24 layer quarter-wave stack coatings on fused silica for HR at normal incidence. We used IAD for the coatings of Tests 1, 3 and 4 and, for comparison, non-IAD for the coating of Test 2. Tests 5 and 6 are, respectively, Ppol and Spol LIDT tests at 32° AOI of a 30 layer HR quarter-wave stack on fused silica; and Tests 7 and 8 are similar Ppol and Spol LIDT tests of an identical 30 layer HR coating on BK7. Figure 3 follows the format of Figs. 1 and 2 including the same horizontal Fail NP Threshold arrow. The LIDTs of Tests 1, 3 and 4 for the IAD coatings at normal incidence show two different behaviors. Test 1 shows no damage (P or NP) out to its fluence limit of 75 J/cm^2 while Tests 3 and 4 LIDTs are more modest (~ 56 J/cm^2 and ~ 37 J/cm^2, respectively) and are based on the Fail NP criterion. The non-IAD 24 layer coating is like its Test 1 IAD counterpart, with ~ 82 J/cm^2 LIDT based on the Fail P criterion with only 3 cumulative NP damage sites. Similar high LIDT, Fail P behavior also applies to the 30 layer IAD HR 32° AOI coatings of Tests 5 – 8. Their LIDTs, from ~ 79 J/cm^2 to ~ 88 J/cm^2, do not correlate to polarization or to substrate, whether fused silica or BK7.

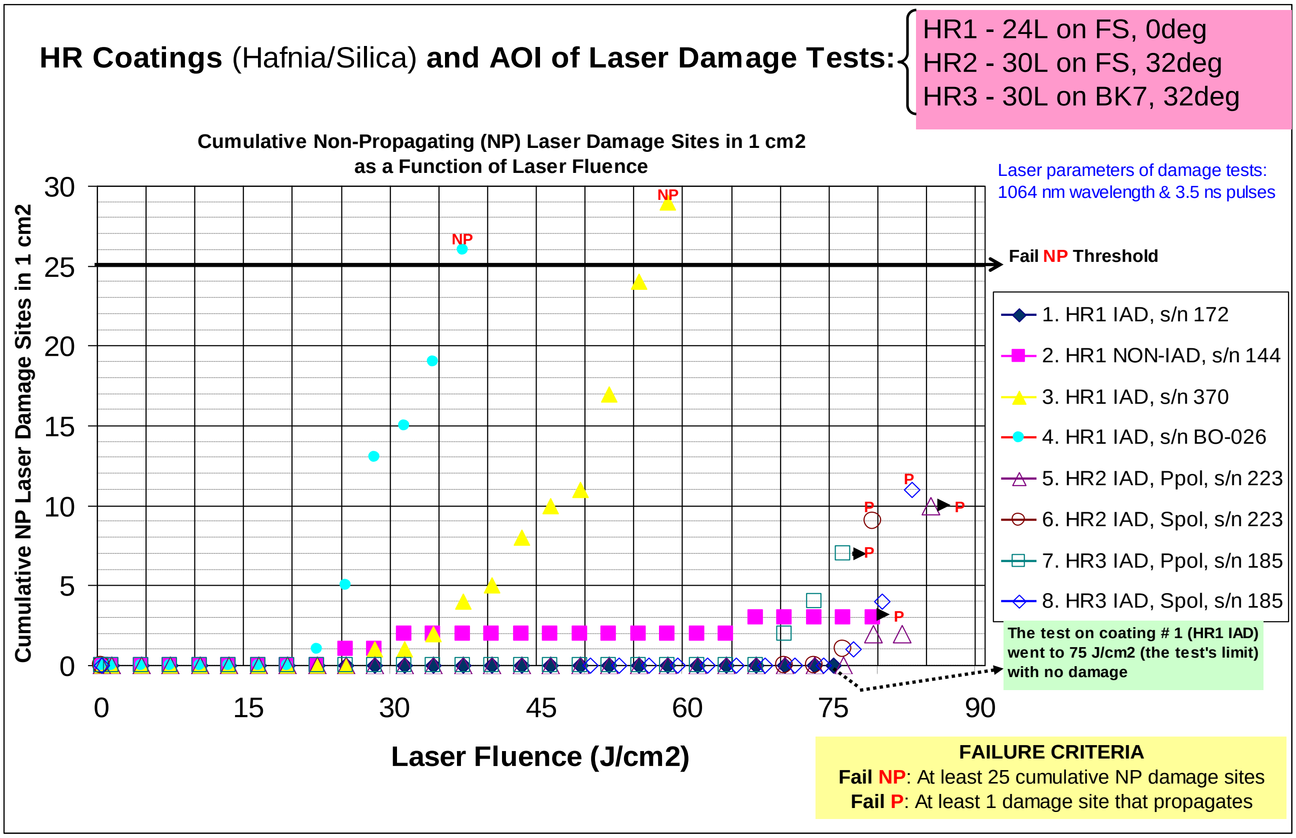


Figure 3. LIDT test results for 7 IAD HR coatings deposited on fused silica (FS) or BK7 as indicated with the chamber at 70 ^oC and the ion beam on continuously, and for 1 non-IAD coating deposited on fused silica with the chamber at 200 ^oC.

The representative results of Figs. 2 and 3 give us confidence that our non-IAD and IAD coating processes reliably lead to HR coatings of high (> 70 J/cm^2) LIDT of Fail P type in conjunction with just a few NP damage sites, and only occasionally lead to HR coatings of moderate (> 35 J/cm^2) LIDT of Fail NP type. Figure 4 shows the calculated optical electric field intensity in the coating layers due to interference of forward and backward propagating components of light during reflection for a 32 layer quarter-wave stack HR design. For some coating designs, resonant intensities many times the incident light intensity can occur in coating layers and at their boundaries [4]. This is not the case for the quarter-wave HR coating of Fig. 4. Instead, its optical electric field intensity maxima quench rapidly into the coating, progressing from ~ 140% of the incident intensity in the outermost silica layer to < 100% at the 2nd layer interface and on down to < 10% beyond the 11th layer in from the coating surface. This electric field behavior favors high LIDT [4] and is a key factor responsible for the high LIDTs of the HR coatings of Figs. 2 and 3 which are of the same design as that of Fig. 4. The thicker outermost silica layer of these coatings is a feature that enhances this type of electric field pattern.

3. REDUCING SURFACE ROUGHNESS OF IAD COATINGS

As we have pointed out, IAD HR coatings on fused silica substrates in vacuum play an important role for lasers of the ZBacklighter class. The usefulness of IAD derives primarily from the increased coating density it provides. The higher the coating density, the lower the stress mismatch tends to be between coating and substrate [4], with corresponding decrease in risk of coating de-lamination due to stress. On the down side, our IAD coatings tend to be rougher than their non-IAD counterparts. So, for IAD we have lower coating stress and risk of coating de-lamination at the expense of higher coating roughness, and vice versa for non-IAD. These factors are a strong motivation for finding ways of reducing, on one hand, the surface roughness of IAD coatings and, on the other hand, the coating/substrate stress mismatch of non-IAD coatings, thereby obtaining the benefits of each without their drawbacks. It is, in fact, possible to

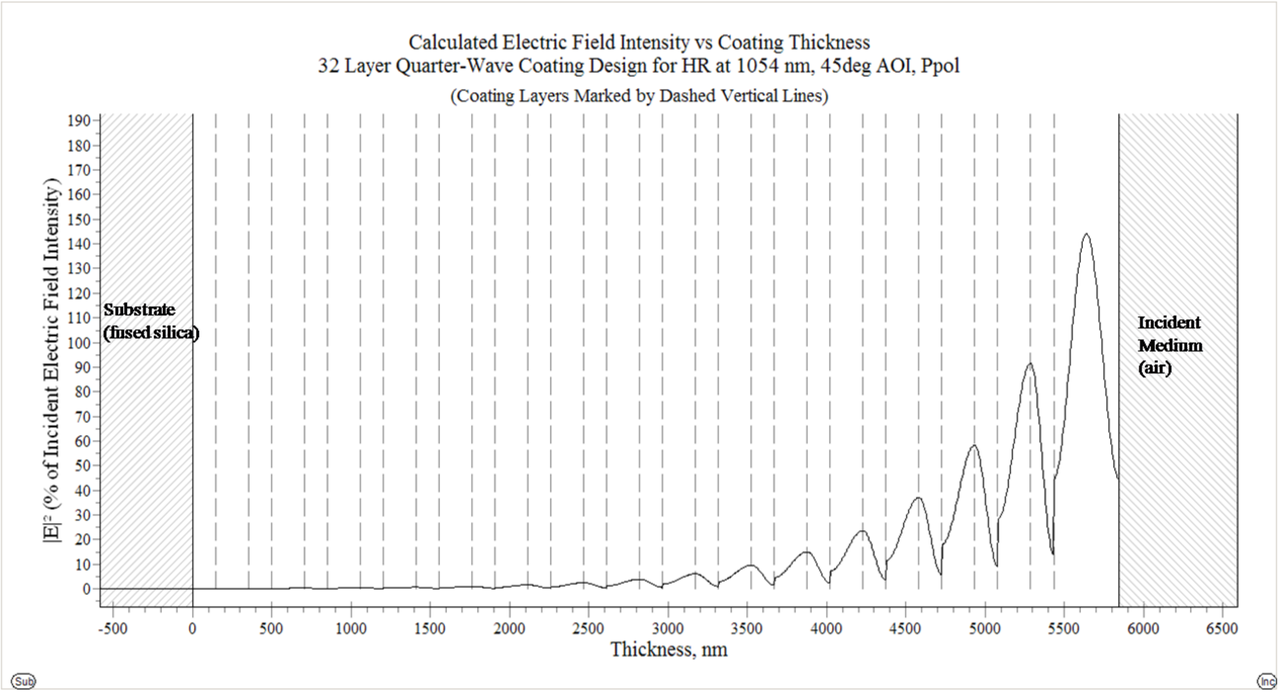


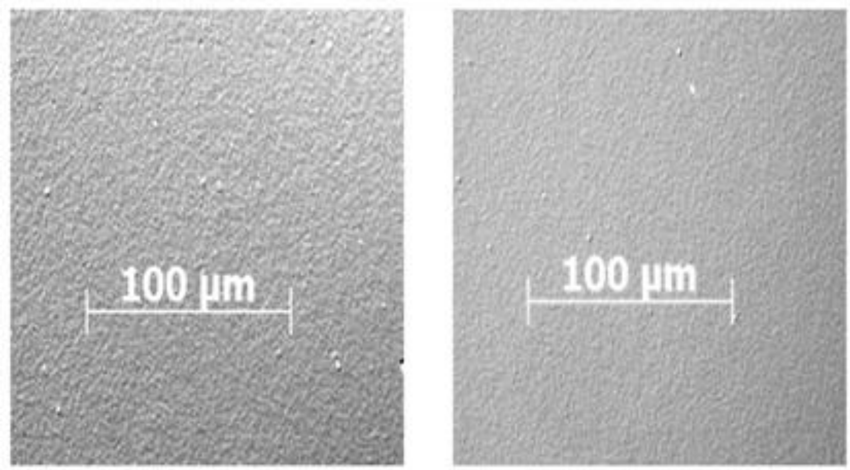
Figure 4. Calculated optical electric field intensity within a 32 layer quarter-wave HR coating during reflection at 1054 nm, 45^o AOI, Ppol, consistent with the coating design.

reduce the higher stress of non-IAD coatings in the case of BK7 substrates. BK7's thermal expansion is large enough that, as long as the substrate is at high temperature of ~ 200 ^{o}C during the non-IAD deposition, its contraction on cooling is sufficient to relieve the higher stress of the coating. Such a stress relief mechanism does not work for fused silica because of its low thermal expansion, only ~ 1/10 that of BK7. The corresponding contraction of the substrate when it cools, even from high temperature, is insufficient to provide adequate coating stress relief. For this reason, IAD is the only way of producing lower stress HR coatings on fused silica. It is based on these considerations that we use non-IAD with the chamber at ~ 200 ^{o}C for HR coatings on BK7, and IAD for HR coatings on fused silica.

This leaves us facing the problem of how to reduce the surface roughness of IAD coatings. One approach to do this is to run the coating process at moderately elevated chamber temperature and also to turn off the ion beam during the pause in deposition between coating layers [6]. We had been doing IAD coatings with the ion beam on continuously and the chamber at 70 ^{o}C, which is the ambient temperature for IAD because the ion bombardment alone keeps the substrate surface at ~ 70 ^{o}C in our case. So, we tried some IAD runs at a higher temperature of ~ 120 ^{o}C with the ion beam turned off during the pause in deposition between layers.

Our first comparison of surface roughness of IAD coatings was of microscope images of the surfaces, displayed by Fig. 5, for two coatings of identical 32 layer quarter-wave stacks for HR at 1054 nm, 45^o AOI, Ppol, but produced under these differing conditions of the IAD process. One coating, coating A of Fig. 5, was on BK7 with the chamber at 70 ^{o}C and the ion beam on between coating layers. The other coating, coating B of Fig. 5, was on fused silica with the chamber at 120 ^{o}C and the ion beam off between layers. We refer to these two ion beam formats as Ib ON and Ib OFF, respectively. From Fig. 5, the surface of coating B definitely appears to be smoother with finer grain features than that of coating A. This initial qualitative comparison raised our interest and curiosity. How would the surface roughness of coating A compare quantitatively with that of coating B from AFM scans and from their diffuse scattering impact on reflectivity? If coating B was indeed smoother than coating A, was it because of the elevated chamber temperature, the Ib OFF format, or both? Also, would the good LIDTs of Fig. 3, for IAD HR coatings produced at 70 ^{o}C with the ion beam on continuously (i.e., Ib ON format), still hold for coatings produced at higher temperatures in the Ib OFF format?

As a first step in answering these questions, we obtained, at Sandia's Nanomaterials Sciences Department (NSD), AFM measurements of RMS surface roughness of two 32 layer IAD coatings just like coatings A and B of Fig. 5 but from different coating runs. We also included for reference a measurement of surface roughness of an identical 32 layer coating, but deposited by non-IAD on BK7 at 200 ^oC. Indeed, for the IAD coating deposited at 70 ^oC in the Ib ON format, the average RMS surface roughness was 6.83 nm (from 3 10 μm x 10 μm AFM scans) while, for the one deposited at 120 ^oC in the Ib OFF format, it was ~ 24 % lower, at 5.20 nm (from 2 similar scans). For the non-IAD reference coating, the RMS roughness (from a single, similar scan) was even lower, at 3.45 nm. These AFM results, which we label by NSD for the laboratory in which they were obtained, show interesting trends. We investigated these trends more systematically using the same non-IAD reference coating together with 6 other IAD coatings of the same 32 layer HR design as the coatings of Fig. 5. The 6 IAD coatings were on fused silica with deposition at temperatures of 70 ^oC, 95 ^oC and 120 ^oC with Ib ON and OFF formats at each temperature, and we evaluated their RMS surface roughness, reflectivity and LIDT.



A. 70 ^oC chamber temperature, Ib ON　　B. 120 ^oC chamber temperature, Ib OFF

Figure 5. Microscope images of surfaces of 2 IAD coatings, A and B, of the same 32 layer quarter-wave design for HR at 1054 nm, 45^o AOI, Ppol but produced with different IAD conditions as indicated. Ib ON/OFF means the ion beam is ON/OFF during the deposition pause between layers.

These AFM surface roughness scans were performed at the Advanced Materials Laboratory (AML) sponsored jointly by University of New Mexico (UNM) and Sandia, and we label them by AML. The AFM instrument is an ASYLUM MFP-3D with AC160TS cantilever tip of < 10 nm radius. The scans were 10 μm x 10 μm (1024 x 1024 points) at 1 Hz scan rate with 2 V (~ 200 nm) free air amplitude, 1.5 V tapping mode amplitude and (- 10 %) off-peak tuning frequency. The cantilever phase was < 90^o for all scans indicating absence of contact/off-contact switching of the tip during the scans. Figure 6 displays the RMS surface roughness values and their average for each coating as identified by its deposition temperature and ion beam status. The results for the non-IAD reference coating are ~ 3.6 nm on average from these AML scans, consistent with the NSD result of 3.45 nm for the same coating. The other AML/NSD comparisons are for the IAD coatings deposited at 70 ^oC in Ib ON format and at 120 ^oC in Ib OFF format, for which the NSD and AML results in each deposition case are for coatings of the same design but different coating runs. In the 70 ^oC, Ib ON case, the NSD RMS roughness values on average are ~ 1.5 nm less than the AML values of Fig. 6 (~ 6.8 nm vs.~ 8.3 nm) while, in the 120 ^oC, Ib OFF case, they are only ~ 0.3 nm less (~ 5.2 nm vs. ~ 5.5 nm). This shows good agreement for HR coatings of the same design from different coating runs and measured by different AFM instruments.

The average of the Ib OFF and ON RMS surface roughness values of Fig. 6 at each temperature shows a definite trend. Namely, it decreases slightly, by ~ 6.3 % (from ~ 8 nm to ~ 7.5 nm), between the 70 ^oC and 95 ^oC coatings but decreases by a much larger amount, ~ 20 % (from ~ 7.5 nm to ~ 6 nm), between the 95 ^oC and 120 ^oC coatings, for an overall decrease of ~ 25%. This confirms that elevating the chamber temperature leads, by itself, to smoother IAD coatings, and that the effect is much more pronounced as temperatures push beyond ~ 95 ^oC. For 70 ^oC deposition, the Ib ON coating is a little rougher on average than the Ib OFF coating while it is the opposite at 95 ^oC, with the Ib OFF coating a little rougher than the Ib ON coating. On the other hand, at 120 ^oC the Ib OFF RMS coating roughness (~ 5.5 nm on average) is markedly less, by ~ 15%, than its Ib ON counterpart (~ 6.5 nm). Thus, the Ib OFF format in comparison to the Ib ON format provides a significant reduction in coating surface roughness for IAD at high chamber temperature of 120 ^oC but not at lower chamber temperatures. This is an important result, that the high temperature regime which yields reduced surface roughness of IAD coatings is one in which the smoothest of these smoother coating surfaces are provided by the Ib OFF rather than Ib ON format.

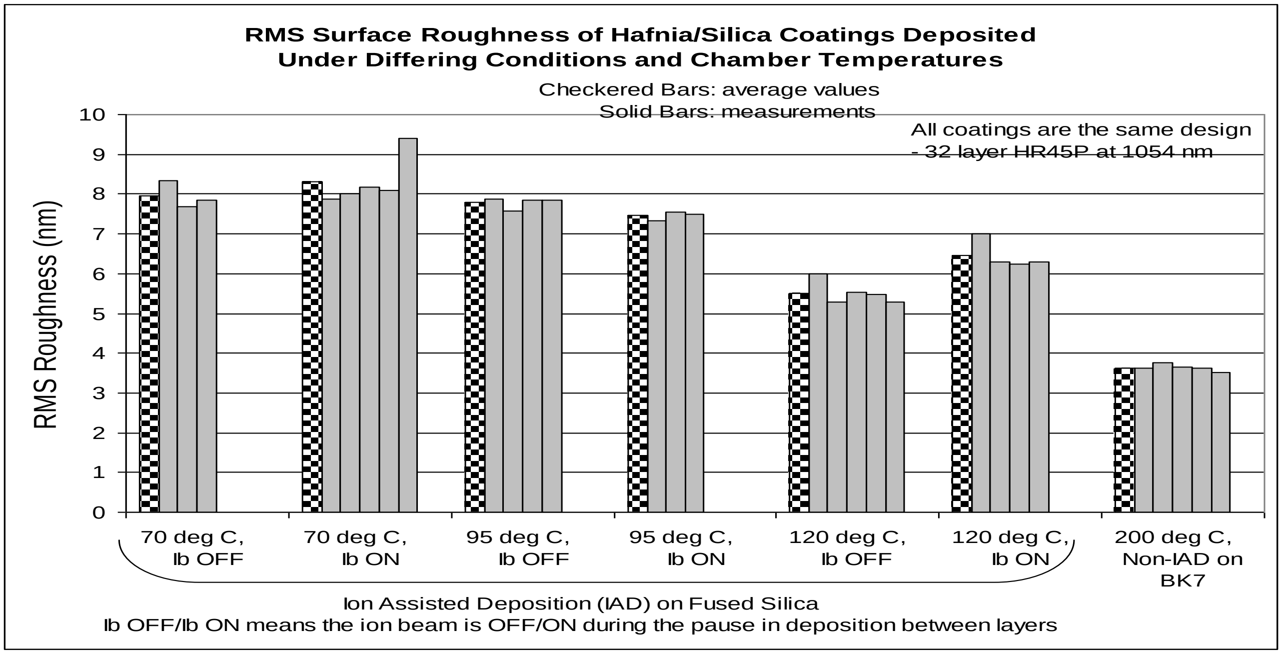


Figure 6. Results of AFM RMS surface roughness scans performed at the UNM/Sandia AML on 7 HR coatings, 6 IAD and 1 non-IAD as indicated, and all of the same design as those of Fig. 5. For each coating, the solid bars show the scan results and the checkered bar shows their average value.

For AFM, factors such as the probe tip radius and scan area relative to the dimensions, both vertical and lateral, of the surface roughness features influence the measure of surface roughness. We took account of these factors in our choice of 10 μm x 10 μm scans with 10 nm tip radius. This scan area is large enough to include a realistic range of surface roughness features, and this tip radius is a good match to their dimensions. We confirmed this with other measures of surface roughness; by AFM with smaller scan areas at the Sandia NSD, and by optical profilometry with a WYKO 2-D instrument at Plymouth Grating Laboratory. The NSD AFM measurements with smaller scan areas yielded correspondingly smaller values of surface roughness, indicating that the smaller scan areas simply include increasingly smaller and thus non-representative ranges of roughness features. The optical profilometry yielded RMS roughness values of ~ 1 nm with no differences due to coating temperature and ion beam format, indicating that, with its probe of surfaces on the scale of visible wavelengths over dimensions of a few hundred μm, it also is not representative for the roughness features of our coatings. Ultimately, the key issue is how much the surface roughness degrades a coating's optical performance, in our case, its reflectivity and LIDT, which we turn to next.

Our reflectivity measurements on the coatings of Fig. 6 are preliminary. With the 32 layer HR design we used for these coatings, they should provide > 99.6 % reflectivity at 1054 nm, 45^o AOI, Ppol. We measured the reflectivities of the Fig. 6 coatings using the Sandia Large Optics Reflectometer in a modified arrangement that excludes diffusely reflected light resulting from surface roughness. This diffuse light tends to emerge from the point of incidence at large angles to the direction of specular reflection. In our modified arrangement, we reduce the aperture diameter of the integrating sphere detector from 1" to ¼" by means of an iris aperture. In this way, diffusely reflected light outside the small cone of angles defined by the ¼" aperture and centered about the direction of specular reflection misses the detector and doesn't contribute to the measured reflectivity. Such reflectivity measurements thus decrease with increased large angle diffuse reflection, which in turn correlates with increased surface roughness. In this context, we expect reflectivities measured with the modified reflectometer arrangement to be higher for the smoother IAD coatings, and vice versa. The results, shown in Fig. 7, confirm this but not without exceptions. For example, of the two 120 ^{o}C IAD coatings, the smoother, Ib OFF one has lower reflectivity (98.87%) than the rougher, Ib ON one (99.0%), which we wouldn't expect. Yet each of these reflectivities exceeds those of their rougher, lower temperature counterparts, consistent with our expectation. Particularly counterintuitive is that the smoothest coating, the non-IAD 200 ^{o}C coating, has, at 98.18%, the lowest measured reflectivity of all. Sorting out these behaviors dependent on differences in surface roughness structures and their diffuse reflection requires further investigation. The reflectivities of the smoother, 120 ^{o}C Ib ON and OFF IAD coatings, at 98.87% and 99.0%, are between ~ 0.1% and ~ 0.4% higher than the reflectivities of the rougher 70 ^{o}C and 95

°C IAD coatings, which range from ~ 98.6% to ~ 98.8%. Such reflectivity gains afforded by smoother coatings obtained with IAD at high chamber temperature constitute reductions of reflection losses that are important for high energy lasers.

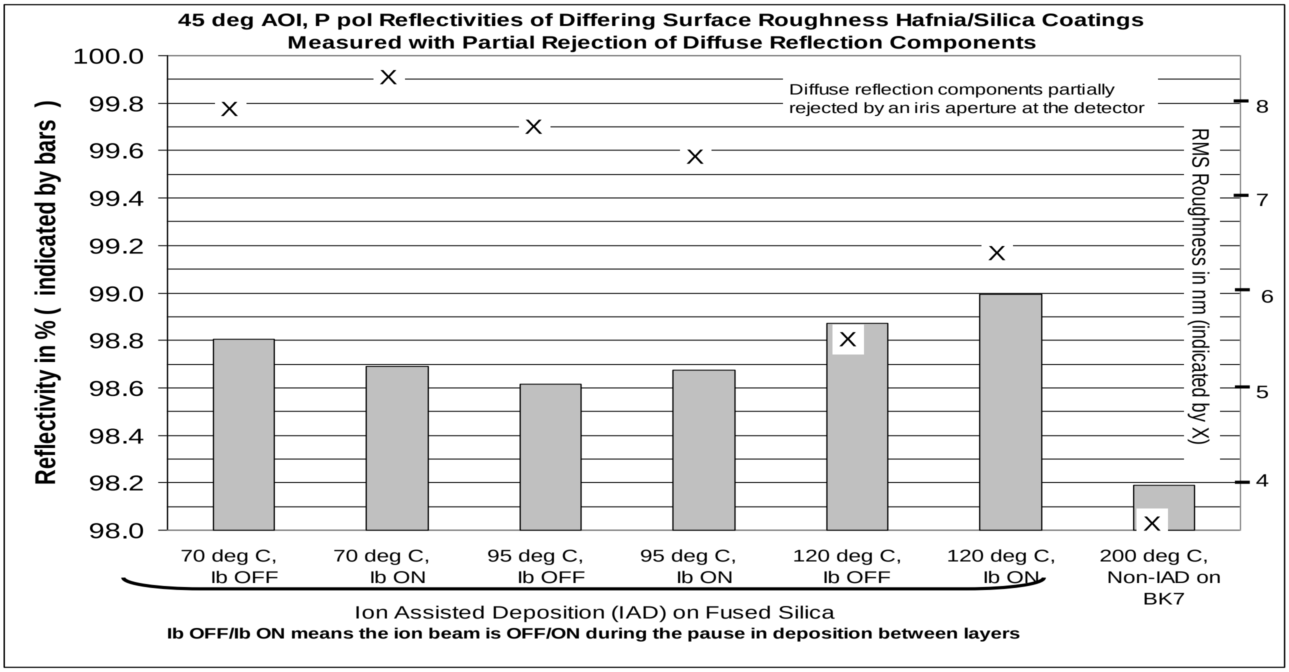


Figure 7. Reflectivities at 1054 nm, 45° AOI, Ppol measured with partial rejection of diffuse reflection for the Fig. 6 coatings of different deposition conditions and surface roughness values as indicated.

Figure 8 displays LIDT test results for the coatings of Fig. 6. The tests were at 1064 nm, 45° AOI, Ppol and show in all cases high levels of laser damage resistance. In 3 cases, Tests 1, 2 and 6 of Fig. 8, the LIDTs are due to the Fail P criterion and range from ~ 58 J/cm^2 to ~ 91 J/cm^2. In the other cases, Tests 3, 4, 5 and 7, neither a Fail P nor a Fail NP criterion was met by the fluences out to the test limits, which ranged from ~ 88 J/cm^2 to ~ 97 J/cm^2. These results

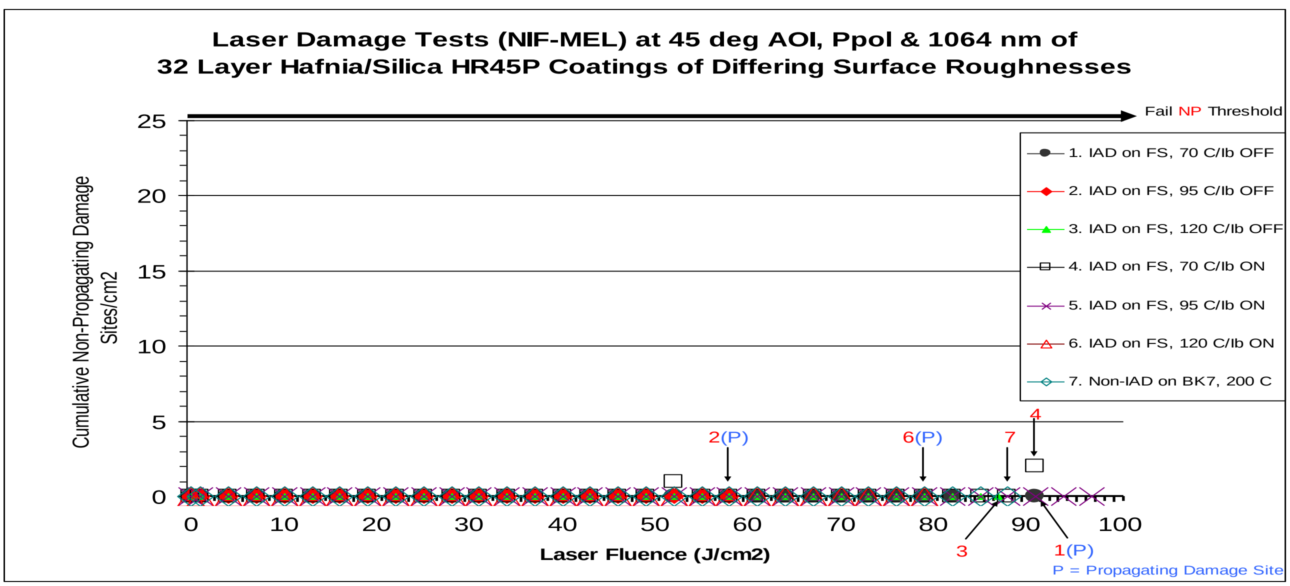


Figure 8. Results of LIDT tests at 1064 nm, 45° AOI, Ppol of the Fig. 6 coatings of different deposition conditions and surface roughness values as indicated (see text).

indicate that our IAD HR coatings remain highly damage resistant to ns pulses at 1064 nm irrespective of chamber temperature out to 120 ^{o}C and of Ib ON or OFF formats for the IAD coating process.

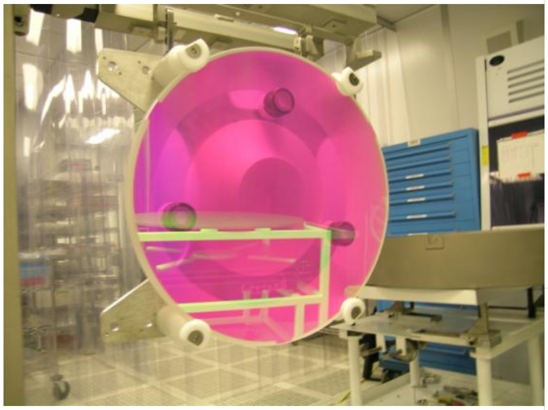
4. THE PW FOA STEERING MIRROR, AND CONCLUSION

The PW FOA steering mirror is a key optic in the next generation Zbacklighter laser beam train. The performance specifications of its coating pose challenges well beyond what we normally face and provide a fitting test of our capabilities in coating design and production of high LIDT, smooth IAD HR coatings. The mirror is a fused silica substrate 75 cm in diameter with a sculpted back surface and corresponding thickness ranging from ~ 3 cm at the edge to a maximum of ~ 15 cm in an annular zone centered about the optic axis. It weighs ~ 200 lb., and will be the final optic steering the ZBacklighter laser beams to focus. Its use environment is in vacuum so, as we've already discussed regarding fused silica, its mirror coating needs to be IAD. The reflectivity performance requirements of its HR coating are very demanding: R for Ppol and Spol > 99.6 % for AOIs from 24^{o} to 47^{o} and for both a ZBeamlet 2ω wavelength band, 527 nm +/- 3 nm, and a ZPetawatt 1ω wavelength band, 1054 nm +/- 6 nm. Furthermore, the coating's LIDT must allow it to handle the ns as well as sub-ps pulses of the ZBacklighter lasers: LIDT > 2 J/cm^{2} for the sub-ps ZPetawatt laser pulses at 1054 nm, and LIDT > 10 J/cm^{2} for the ns ZBeamlet laser pulses at 527 nm.

In considering the design and production of this high performing HR coating, we referenced against quarter-wave type coatings like those we have discussed so far. As to production, a 32 layer coating requires on the order of 6 hours deposition time in our large optics coater. We did not want the high performing HR coating to have many more layers than this because the risks of unforeseen process and/or coating problems tend to increase with the number of coating layers and the coating process time. As to design, we knew the PW FOA steering mirror coating would need to be non-quarter-wave to meet the demanding performance requirements of dual wavelength HR and high LIDT over such a wide range of AOIs. Our design process relied on the OptiLayer thin film software (http://www.optilayer.com/) which proved to be a very effective tool for exploring non-quarter-wave-stack options. We converged on a 50 layer coating design. It provided the required HR behaviors, and also the electric field behavior described in Sect. 2 that is favorable to high LIDT (see Fig. 4). As we mentioned in Sect. 2, this electric field behavior obtains at the single design wavelength and AOI for HR of quarter-wave coatings. But it is not necessarily common at the widely separate wavelength bands and broad ranges of AOIs for HR, as provided by non-quarter-wave coating designs that would meet the PW FOA steering mirror requirements.

Our product coating run for the 50 layer PW FOA steering mirror coating used IAD and we applied the 120^{o} C, Ib OFF conditions that had provided the smoothest of the 32 layer quarter-wave IAD coatings of Fig. 6. The RMS surface roughness of the 50 layer product coating, in an average of 4 AFM 10 μm x 10 μm scans on the AML instrument, is 6.395 nm, a value which is reasonably low, within 1 nm of its counterpart for the 32 layer quarter-wave coating of Fig. 6. This confirms that the 120^{o} C, Ib OFF conditions provided their surface smoothing effects for this 50 layer IAD coating. Figure 9 shows the coated PW FOA steering mirror along with transmission spectra of its coating. The spectra as designed (obtained by calculation) and as coated (obtained by measurement on a Lambda 950 spectrophotometer) are for Ppol at 24^{o} and 47^{o} AOIs. These are the extremes of the range of AOIs over which the coating provides high reflectivity at both 527 nm and 1054 nm. The spectrum of the coating as deposited matches that of the design well at these AOI extremes, and the match is equally good at the AOIs in between. We also include in Fig. 9 the coating's LIDTs from 532 nm, Ppol tests with 3.5 ns laser pulses at 25^{o} and 45^{o} AOIs, near the AOI extremes. These LIDTs, 16 J/cm^{2} and 19 J/cm^{2}, respectively, exceed the 2.5 – 10 J/cm^{2} fluences of the ns, 527 nm (2ω) ZBeamlet laser pulses by a fair margin. We have measured the LIDT of this 50 layer coating in-house with 400 fs pulses to be 1.38 J/cm^{2} at 1054 nm, 35^{o} AOI, Ppol [5]. This result is promising since the LIDT should scale up for the longer (500 – 700 fs) output pulses of the ZPetawatt laser and possibly match its eventual 2.5 – 4 J/cm^{2} fluences.

In conclusion, we have presented results of NIF-MEL LIDT tests with 3.5 ns pulses at 1064nm and 532 nm on a large number of AR and HR coatings produced at Sandia's Large Optics Coating Operation. The LIDTs of these coatings range from a few tens to many tens of J/cm^{2} and in all cases exceed by good margins the fluence levels of the ns class pulses of the ZBacklighter lasers. We discussed the issues of stress and surface roughness for non-IAD and IAD HR coatings and reported on an investigation into how the surface roughness of our IAD coatings depends on the coating process conditions of chamber temperature and ion beam status, either on or off, during the pause in deposition between



PW FOA steering mirror as coated

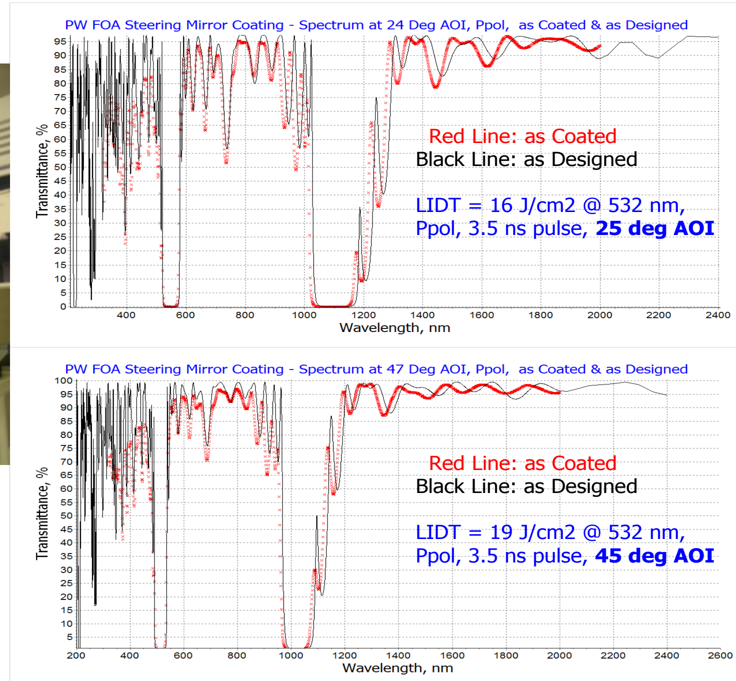


Figure 9. The PW FOA steering mirror, with spectra and LIDTs for its 50 layer, non-quarter-wave, HR coating at extremes of its 24^{o} - 47^{o} AOI performance range. Spectra as coated are spectrophotometer measurements and those as designed are calculations.

coating layers. The reported AFM measurements show that ~ 25 % reduction in surface roughness of IAD HR coatings is achieved by elevating the temperature from ambient, at ~ 70 ^{o}C, to ~ 120 ^{o}C in conjunction with turning the ion beam off between layers during the coating run. Reflectivity measurements with partial rejection of diffusely reflected light confirm the improved surface smoothness. The IAD coatings exhibit excellent LIDT regardless of chamber temperature or ion beam status during deposition. All aspects of our coating capabilities came to bear on the 75 cm diameter PW FOA steering mirror coating with its demanding requirements of HR and high LIDT for 1054 nm and 527 nm at AOIs from 24^{o} to 47^{o}. We developed a 50 layer design for this coating, and successfully deposited the coating on the mirror substrate by IAD at 120 ^{o}C with the ion beam off between layers. Spectra, LIDT tests and AFM scans of the coating confirm that it meets the performance requirements for HR and for laser damage resistance to ns pulses at 532 nm, and also has the reduced surface roughness that we expected.

Acknowledgement: Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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