40th ANNUAL BOULDER DAMAGE SYMPOSIUM
Proceedings

LASER-INDUCED DAMAGE IN OPTICAL MATERIALS: 2008

22–24 September 2008
Boulder, Colorado

Editors
Gregory J. Exarhos, Detlev Ristau, M. J. Soileau, Christopher J. Stolz

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THIN FILM

MATERIALS AND MEASUREMENTS

MINI-SYMPOSIUM: DAMAGE TO FUSED SILICA

International Program Committee

The cochairs of this series of symposia rely heavily on an International Program Committee to ensure their awareness of significant research in the broad field of laser-induced damage throughout the world. Its members are also frequently the source of suggestions for invited speakers and mini-symposium topics and leaders. The committee performs a vital service as an outreach for the conference on a global scale. Individuals with suggestions for the meeting are requested to contact any committee member (next page) who is either an acquaintance or in close proximity. The committee is ably led by Detlev Ristau, International Program Committee Chair.

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International Program Committee

Symposium Welcome

On the occasion of the 40^{th} Boulder Damage Symposium

Detlev Ristau
Laser Zentrum Hannover e.V. (Germany)

On behalf of my fellow cochairs, Greg Exarhos, M. J. Soileau, and Chris Stolz, I extend a hearty welcome to all participants to the 40^{th} Annual Symposium on Optical Materials for High-Power Lasers. Forty years have passed since the first Conference which was started by Dr. Art Guenther and Dr. Alex Glass following the idea to join forces in the field of high power materials for laser applications. In those days research in laser materials and optical components was considered as a transient activity with clear targets to be achieved in a finite time period. An example characteristically reflecting this attitude is the following opinion advanced by one of the cofounders, Dr. Alex Glass, on the occasion of the 10-year anniversary of the conference:

"It is my annual hope that each year's symposium will be the last."

However, in the course of the rapid development of laser technology towards ever increasing output power and beam quality, laser-induced damage in optical materials is continuing to be one of the key issues in fundamental research, technological development, and industry. Nowadays, laser systems can be found in nearly every advanced product or application, and the enormous potential of laser technology is far from being exhausted. The Boulder Damage Conference is a clear indicator of this evolution, having featured many tremendous efforts of the scientific community over the last forty years. Once again, the conference attracted many scientists from all over the world (see Fig. 1), who contributed to the major topics of the conference and did lively networking at the NIST facility in Boulder, Colorado. The series of the conference proceedings published by the SPIE reflects the enormous vitality of the field, and can be considered as the major resource compiled in the laser damage field from its early stages onwards. The tremendous efforts of the authors to prepare the manuscripts and posters are gratefully acknowledged here.

The international nature of the BDS has always been extensively supported by an International Program Committee representing research activities in different countries. Presently, the International Program Committee consists of representatives from the United Kingdom, France, Russia, Japan, Germany and the United States of America. Representing one of the nations with enormous progress in optical technology, scientists from China have joined the program committee this year. In addition to providing contributions to the conference program, the International Program Committee is also active in promoting the conference and in attracting researchers from around the world. The engagement of the International Program Committee, which initiated participation from more than 30 countries during the last several years, is acknowledged here as being very important.

Following tradition, the Boulder Damage Symposium addresses four core topics including materials and measurements, fundamental mechanisms, thin films, as well as surfaces and mirrors. The 40^{th} anniversary conference programme featured special plenary talks reviewing most important developments and results reported during the past conferences. In order to further inspire the scientific dialogue at the conference, a mini-symposium dedicated to a current topic in laser material interaction is organized every year. The 40^{th} Boulder Damage Conference features a mini-symposium on “Damage to Fused Silica” with interesting contributions from industrial companies and research institutes from France, Japan, the United States of America, and Germany. For the first time, a damage competition was organized by Chris Stolz aimed to review the present state of the art in high reflecting coatings for the Nd:YAG laser. This initiative found a tremendous resonance within the community and resulted in 35 samples submitted by companies and research institutes from China, Japan, Germany, Lithuania, and the United States of America. Sample testing was performed by Mike Thomas at Spica Technologies Inc., who accomplished an enormous amount of work by evaluating all samples with respect to laser induced damage. This outstanding effort is appreciated by the community, and the organizers acknowledge this special contribution by Mike Thomas. Chris Stolz has prepared a summary paper on the competition which can be found in this proceedings volume of the conference.

Much of the success of the meeting can be attributed to the untiring efforts of the SPIE staff as well as Chris Stolz, conference treasurer. The organizers also acknowledge the efforts of the NIST staff, Gordon Day, Wendy Orthega, and especially, Kent Rochford (NIST-Coordinator) for coordinating the activities and arranging for the audio-video facilities in the meeting room. We also appreciate the co-sponsoring from the Lawrence Livermore Laboratory, the Pacific Northwest National Laboratory, and especially, Spica Technologies for performing the damage tests for the competition.

Fig. 1: Attendees of the 40th Boulder Damage Symposium joining for the traditional conference wine and cheese reception on the stairway to the National Center for Atmospheric Research in Boulder.

Summary of Meeting

Laser-Induced Damage in Optical Materials
40th Annual Symposium
22–24 September 2008

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Livermore, CA 94551 USA

1. Abstract

This proceedings volume contains the papers presented as oral and poster presentations at the 40th Annual Symposium on Optical Materials for High-Power Lasers. The conference was held at the National Institute of Standards and Technology facility in Boulder, Colorado on 22–24 September 2008. The symposium was divided into the traditional sessions devoted to the following topics: thin films; surfaces, mirrors and contamination; fundamental mechanisms; materials and measurements; and finally, a mini-symposium on fused silica. The conference was opened by Dr. Detlev Ristau with a symposium welcome. Dr. Gregory J. Exarhos of Pacific Northwest National Laboratory (USA), Dr. Detlev Ristau of the Laser Zentrum Hannover e.V. (Germany), Dr. M. J. Soileau, of the University of Central Florida (USA), and Mr. Christopher J. Stolz of the Lawrence Livermore National Laboratory (USA), co-chaired the symposium. The founding organizers are Dr. Arthur H. Guenther and Dr. Alexander J. Glass. This year, a DVD will be released which will include all of the papers from the 1968–2008 proceedings.

All told, 66 papers were presented, including oral and poster presentations plus a mini-symposium. No parallel sessions were held allowing the opportunity to discuss common research interests with all the presenters. With 145 participants attending, the meeting offered an opportunity to make many new acquaintances. Although held annually in the U.S., this is a truly international conference with 30 percent of the attendees and 55 percent of the presentations coming from abroad. As usual, the National Institute of Standards and Technology in Boulder, Colorado, offered a setting conducive to interchanges between individuals working in closely related and complementary fields. We look forward to future opportunities to come together again in this setting.

The 41st Annual Symposium of this series will be held in Boulder, Colorado, 21–23 September 2009. A concerted effort will be made to ensure a close liaison between the high-peak-power and high-average-power communities, as well as to include damage issues related to various research efforts and commercial laser applications. A mini-symposium related to the subject of femtosecond lasers is anticipated. Invited talks are also anticipated to open the four major topical areas:

The principal topics to be considered as contributed papers in 2009 do not differ drastically from those enumerated above. We expect to hear more about the impacts of contamination on the laser resistance of optical components and the impacts of defects since both of these topics continue to generate significant interest. High-energy laser windows, crystals, and transparent ceramics continue to place limitations on laser systems and so remain an active area of research and spirited debate. Refinement of the mitigation strategy consisting of damage initiation followed by arresting damage growth through post-processing techniques while not creating downstream damage is also expected to be a continued focus as a large number of laser-resistant UV optics are manufactured for large-aperture fusion lasers. Short pulse laser optics and damage phenomena remain an active area of research. We also expect to hear more about new measurement techniques to improve our understanding of the different damage mechanisms or to improve the manufacturing of optical materials and thin films for optical components of greater laser damage resistance.

As was initially established in 1992, several distinguished invited speakers will make presentations of a tutorial or review nature. In addition, other contributors will cover late-breaking developments of interest to the attendees. The purpose of this series of symposia is to exchange information about optical materials for high-power / high-energy lasers. The editors welcome comments and criticism from all interested readers relevant to this purpose.

Keywords: laser damage, laser interaction, optical components, optical fabrication, optical materials and properties, thin film coatings, contamination.

2. Introduction

The 40th Annual Symposium on Optical Materials for High-Power Lasers (a.k.a. the Boulder Damage Symposium, because of its Boulder, Colorado, venue) was held 22–24 September 2008. This symposium continues to be the principal U.S. and International forum for the exchange of information relative to the interaction of intense laser light with optical media and components. Historically, the meeting has been divided into four broad categories: thin films; fundamental mechanisms; materials and measurements; and surfaces, mirrors, and contamination as illustrated in figure 1.

3. Thin Films

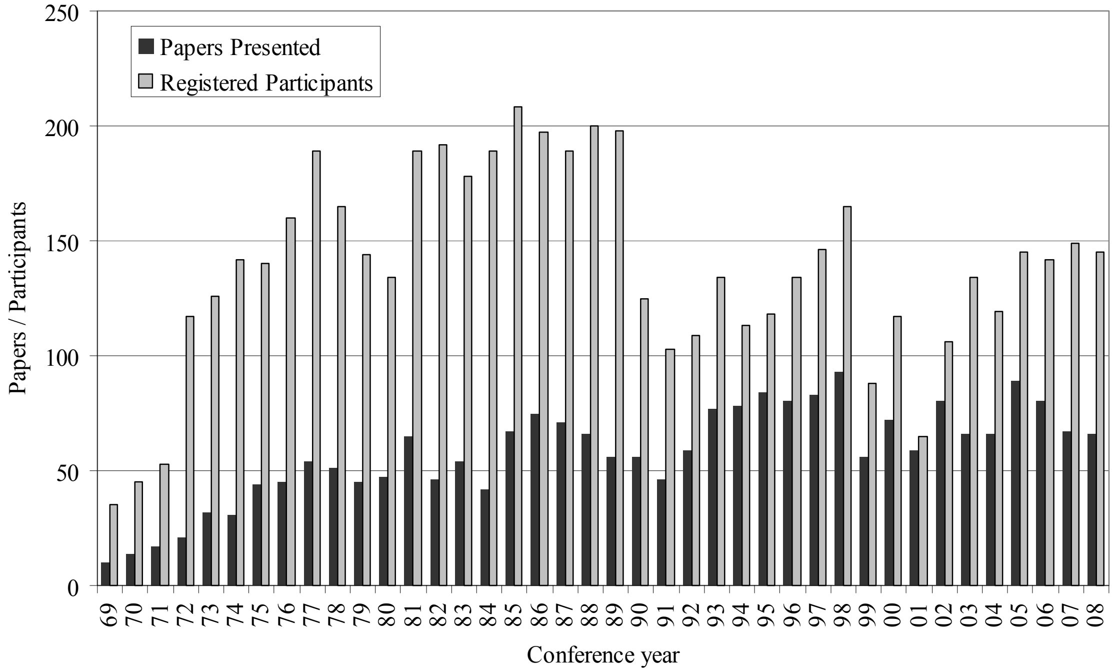
This year, a thin film damage competition was started to sample the industrial, government, and academic sectors producing high laser resistant optical coatings. 1064 nm high reflectors were tested at 5 ns with damage thresholds ranging from 1 to over 100 J/cm^2. A multitude of deposition processes, coating materials, and manufacturing techniques submitted to this competition provided some interesting results that will likely lead to some interesting future research.

Because of the tremendous range of applications of optical multilayers for modifying the optical performance of elements (e.g., reflectivity, wavelength sensitivities, polarization, or simply protection, etc.), this receives attention. Besides damage thresholds or sensitivity, topics include advanced thin deposition technology, film structure, film design, film response to environmental attack and aging, and numerous reports on important film properties such as adhesion, thermal conductivity, absorption, stability, defect identification, aging — drift and moisture infusion, and conditioning processes to improve performance.

Dense thin film processes offer the benefit of environmental stability so much of the research in the field of thin films is proceeding in this direction. Laser interaction studies are uncovering areas were dense films offer advantages over traditional e-beam coatings. Also as shown in the thin film damage competition there are a number of companies that are manufacturing dense coatings from a variety of deposition techniques with very high laser resistance.

Coating defects continue to be an area of active interest in both process optimization to minimize defect formation as well as mitigation techniques such as laser conditioning. This year we continued to see interest in short pulse and DUV coatings.

Boulder conference attendence statistics



Topical emphasis of conference by year

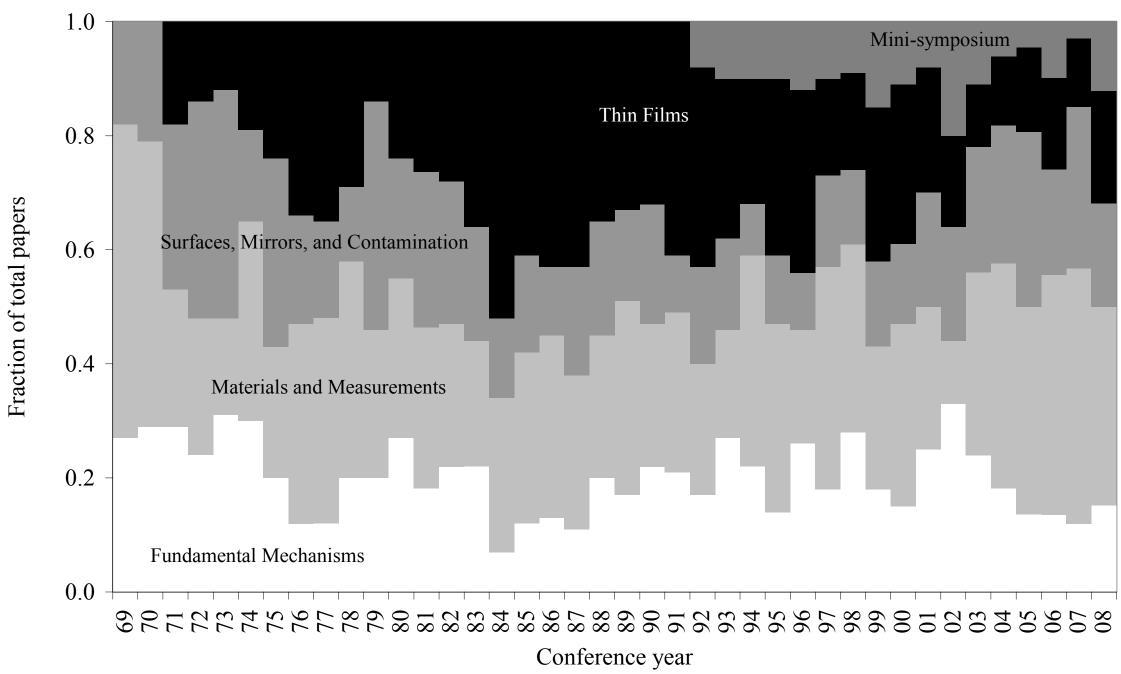


Fig. 1 Historical statistics of conference attendance and paper submission (top) and distribution of submissions by topical area (bottom).

4. Fundamental Mechanisms

This area deals with the interaction of light with matter – where real system experience is presented. Topics include nonlinear behavior, self-focusing, thermal modeling, and experimental data reduction protocols (e.g. effects of pulse width, repetition rate or duty cycle, spot size, wavelength, temperature, ionizing radiation, and other environmental effects), as well as all types of experimental or material variable scaling relationships that not only afford insight into the fundamentals of the interaction process, but allow extrapolations for engineering and cost-benefit evaluations. In many areas, these insights are based on real-world, systems-level tests, as opposed to a frequently pristine laboratory environment.

A significant amount of theoretical work is now being done in the femtosecond regime as exemplified by the significant number of submitted papers on ultrafast phenomenon.

5. Surfaces and Mirrors

Here one will find presentations on surface preparation (including single-point diamond micro-machining and ductile grinding), subsurface damage characterization, roughness and scattering, environmental degradation and aging, as well as substrate material properties, including cooling techniques, and, of course, damage measurements and the cleaning of surfaces. The crux of the contamination problem is fundamentally that damage experiments done in controlled clean laboratory settings do not necessarily yield the same results as laser operations in less pristine operating environments. There is a significant amount of work needed in understanding what contamination is acceptable, what contamination is threatening to optic survivability, and how fluence-limiting or lifetime-limiting contamination can be eliminated or mitigated from operating laser systems.

A fair amount of papers deal with decontamination of optical surfaces and the impact of contamination on laser resistance. Interest in antireflection and bare surface laser resistance also remains high.

6. Materials and Measurements

This section deals with laser damage to the bulk of transparent optical media—whether amorphous, polymeric, polycrystalline, or crystalline—and its preparation, as well as reports of material properties of import to their optical function and/or the damage process, e.g., linear and nonlinear refractive indices, absorption, thermal conductivity, stress-optic coefficients, moduli, and defects. Also included are new techniques for measuring these quantities, which present a continuing challenge as materials are improved in quality and diversity.

There is always interest in improved measurement systems or new instruments particularly in the area of photothermal non-destructive characterization and defect detection instrumentation. Laser damage measurements are difficult and work continues on developing tests that address large area versus small area and the difficulties of obtaining high resolution data. Motivated by a 2007 challenge from cofounder Alex Glass, a spirited talk on error bars was well received

7. Mini-Symposium on Fused Silica

This year the meeting was concluded with a small mini-symposium dealing with the topic of Fused Silica. This material is critical in high power laser systems as a laser resistant transparent material used for beam focusing and environmental barrier. The talks covered a multitude of topics covering both bulk and surface properties, defects, damage mechanisms over a wide range of pulse lengths, and the challenges associated with characterization of this unique material. The mini-symposium was organized this year by Christopher Stolz from Lawrence Livermore National Laboratory (USA) and Hervé Beregol from Commissariat à l'Energie Atomique (France).

8. Keynote Presentations

As part of the 40th anniversary of this meeting keynote presentations were given highlighting 40 years of research presented at BDS in the four major topical areas. They included:

1. “40-year retrospective of fundamental mechanisms,” M. J. Soileau, University of Central Florida (USA).

2. “Laser-induced damage in thin-film optical materials: 1970–2008,” B. E. Newnam, Los Alamos National Laboratory (USA).

3. “Transparent-media characterization dedicated to laser damage studies: a key task, multi-faceted and always renewed,” M. Commandré, Institut Fresnel. (France).

4. “Laser-induced surface damage of optical materials: absorption sources, initiation, growth, and mitigation,” S. Papernov, Laboratory for Laser Energetics (USA).

9. Conference Awards

Beginning with the meeting in 2000, the organizers instituted a best paper award in the oral and poster categories. The awards appropriately take the form of laser-induced art in an optical glass plaque. (see, e.g., paper by I. N. Trotski, Proc. SPIE 4679, 392-399 (2001)).

There were several outstanding posters and oral papers, however, the following papers were selected:

Best oral paper:
“Femtosecond laser breakdown of gases and transparent solid states: ultrafast space-time and spectrum-time resolved diagnostics of multicharged microplasma,” S. V. Garnov, V. Bukin, A. A. Malyutin, and V. Strelkov, A.M. Prokhorov General Physics Institute of Russian Academy of Sciences (Russia).

Best poster paper:
“Investigation of bulk laser damage in transparent YAG ceramics controlled with microstructural refinement,” T. Kamimura, Y. Kawaguchi, T. Arii, W. Shirai, Osaka Institute of Technology, (Japan), T. Mikami, T. Okamoto, Okamoto Optics Co. Ltd. (Japan), Y. L. Aung, A. Ikesue, World Lab. Co. Ltd. (Japan).

10. In Conclusion

The location in Boulder, Colorado, during autumn at the venue of the National Institute of Standards and Technology and its outstanding facilities and support staff were appreciated by all. The 145 attendees were easily accommodated with ample opportunity to mingle and socialize.

The organizers of the Boulder Damage Symposium look for opportunities to join with other related groups for joint meetings in the future. For example, in 2002 we had a joint meeting with the 7th International Workshop on Laser Beam and Optics Characterization, again with no parallel sessions.

We must also take note of the tireless assistance of SPIE staff who handle the administrative functions of the symposium. Their presence, experience, resources, and professionalism clearly were made manifest with on-line reservations, payment by credit cards, badges, preparation of the abstract book and pocket programs, and on-line document service, and to which we may add the social functions—thanks to them, “A good time was had by all.”

11. Acknowledgments

A number of volunteers help tirelessly with some of the administrate duties necessary to put on a conference of this magnitude. Susie McGuire, Administrative Assistant to Greg Exarhos, assists with transcriptions of technical questions asked at the end of each talk. SPIE personnel took care of all the administrative planning and on-site tasks including registration, setup, and general questions and were responsible for the publication of all of the manuscripts into this proceedings volume.

Of course, we are all indebted to Kent Rochford, Division Chief of the Optoelectronics Division, who was the prime contact at NIST, for his continued support and encouragement, and Wendy Ortega, also of NIST, who together made it possible to hold a seamless meeting. On behalf of all the organizers and attendees, we thank them for their tireless efforts.

12. References

Books:

A. J. Glass and A. H. Guenther, eds. *Damage in Laser Glass*, ASTM Spec. Tech. Pub. 469, ASTM, Philadelphia, PA (1969).

N. Bloembergen, *Fundamentals of Damage in Laser Glass*, National Materials Advisory Board Publ. NMAB-271, National Academy of Sciences (1970).

N. Bloembergen, *High-Power Infrared Laser Windows*, National Materials Advisory Board Publ. NMAB-356 (1971).

R. M. Wood, *Laser-Induced Damage in Optical Materials*, Adam Hilger, Bristol (UK) (1986).

M. J. Weber, ed., *Handbook of Laser Science and Technology,* Vol. III: Optical Materials, Part 1: Nonlinear Optical Properties/Radiation Damage, CRC, Boca Raton, FL (1986).

M. J. Weber, ed., *Handbook of Laser Science and Technology,* Vol. IV: Optical Materials, Part 2: Properties, CRC, Boca Raton, FL (1986).

M. J. Weber, ed., *Handbook of Laser Science and Technology,* Vol. V: Optical Materials, Part 3: Applications, Coatings, and Fabrication, CRC, Boca Raton, FL (1987).

R. M. Wood, Ed., *Selected Papers on Laser Damage in Optical Materials*, SPIE Milestone Series Vol. MS24, Bellingham, WA (U.S.) (1990).

M. R. Kozlowski, Damage-Resistant Laser Coatings, in *Thin Films for Optical Systems*, F. Flory, ed., Marcel Dekker, New York, 521-549 (1995).

M. J. Weber, ed., *Handbook of Laser Science and Technology, Suppl. 2, Optical Materials*, CRC, Boca Raton, FL, (1995).

A. H. Guenther, ed., *International Trends in Applied Optics*, SPIE Press monograph, Bellingham, Washington, Chapters 1, 3, 8, 9, 10, & 12 (2002).

M. J. Weber, ed., *Handbook of Optical Materials*, CRC, Boca Raton, FL (2002).

R. M. Wood, *The Power and Energy-Handling Capability of Optical Material, Components, and Systems*, (Tutoriual Texts in Optical Engineering Vol TT60 A. R. Weeks Series Editor SPIE Press Bellingham WA) (2003).

R. M. Wood, *Laser Induced Damage of Optical Materials* (Institute of Physics Publishing, Bistrol, UK) (2003).

C. J. Stolz and F. Y. Génin, Laser Resistant Coatings, in *Optical Interference Coatings*, N. Kaiser and H. Pulker, eds., Springer-Verlag, Berlin, 310-333 (2003).

Proceedings:

A. J. Glass and A. H. Guenther, eds., *Damage in Laser Materials*, Nat. Bur. Stand. (U.S.) Spec. Publ. 341 (1970).

A. J. Glass and A. H. Guenther, Eds., *Damage in Laser Materials: 1971*, Nat. Bur. Stand. (U.S.) Spec. Publ. 356 (1971).

A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: 1972*, Nat. Bur. Stand. (U.S.) Spec. Publ. 372 (1972).

A. J. Glass and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 1973*, Nat. Bur. Stand. (U.S.) Spec. Publ. 387 (1973).

A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: 1974*, Nat. Bur. Stand. (U.S.) Spec. Publ. 414 (1974).

A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: 1975*, Nat. Bur. Stand. (U.S.) Spec. Publ. 435 (1975).

A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: 1976*, Nat. Bur. Stand. (U.S.) Spec. Publ. 462 (1976).

A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: 1977*, Nat. Bur. Stand. (U.S.) Spec. Publ. 509 (1977).

A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: 1978*, Nat. Bur. Stand. (U.S.) Spec. Publ. 541 (1978).

H. E. Bennett, A. J. Glass, A. H. Guenther, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 1979*, Nat. Bur. Stand. (U.S.) Spec. Publ. 568 (1979).
H. E. Bennett, A. J. Glass, A. H. Guenther, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 1980*, Nat. Bur. Stand. (U.S.) Spec. Publ. 620 (1981).
H. E. Bennett, A. J. Glass, A. H. Guenther, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 1981*, Nat. Bur. Stand. (U.S.) Spec. Publ. 638 (1983).
H. E. Bennett, A. H. Guenther, D. Milam, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 1982*, Nat. Bur. Stand. (U.S.) Spec. Publ. 669 (1984).
H. E. Bennett, A. H. Guenther, D. Milam, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 1983*, Nat. Bur. Stand. (U.S.) Spec. Publ. 688 (1985).
H. E. Bennett, A. H. Guenther, D. Milam, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 1984*, Nat. Bur. Stand. (U.S.) Spec. Publ. 727 (1986).
H. E. Bennett, A. H. Guenther, D. Milam, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 1985*, Nat. Bur. Stand. (U.S.) Spec. Publ. 746 (1987).
H. E. Bennett, A. H. Guenther, D. Milam, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 1986*, Nat. Bur. Stand. (U.S.) Spec. Publ. 752 (1987).
H. E. Bennett, A. H. Guenther, D. Milam, B. E. Newnam, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1987*, Nat. Bur. Stand. (U.S.) Spec. Publ. 756 (1988).
H. E. Bennett, A. H. Guenther, B. E. Newnam, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1988*, Nat. Bur. Stand. (U.S.) Spec. Publ. 775 (1989).
H. E. Bennett, L. L. Case, A. H. Guenther, B. E. Newnam, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1989*, NIST (U.S.) Spec. Publ. 801, ASTM STP 1117 and Proc. SPIE 1438 (1989).
H. E. Bennett, L. L. Case, A. H. Guenther, B. E. Newnam, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1990*, ASTM STP 1141 and Proc. SPIE 1441 (1991).
H. E. Bennett, L. L. Case, A. H. Guenther, B. E. Newnam, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1991*, Proc. SPIE 1624 (1992).
H. E. Bennett, L. L. Case, A. H. Guenther, B. E. Newnam, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1992*, Proc. SPIE 1848 (1993).
H. E. Bennett, L. L. Case, A. H. Guenther, B. E. Newnam, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1993*, Proc. SPIE 2114 (1994).
H. E. Bennett, A. H. Guenther, M. R. Kozlowski, B. E. Newnam, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1994*, Proc. SPIE 2428 (1995).
H. E. Bennett, A. H. Guenther, M. R. Kozlowski, B. E. Newnam, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1995*, Proc. SPIE 2714 (1996).
H. E. Bennett, A. H. Guenther, M. R. Kozlowski, B. E. Newnam, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1996*, Proc. SPIE 2966 (1997).
G. J. Exarhos, A. H. Guenther, M. R. Kozlowski, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1997*, Proc. SPIE 3244 (1998).
G. J. Exarhos, A. H. Guenther, M. R. Kozlowski, K. Lewis, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1998*, Proc. SPIE 3578 (1999).
G. J. Exarhos, A. H. Guenther, M. R. Kozlowski, K. Lewis, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 1999*, Proc. SPIE 3902 (2000).
G. J. Exarhos, A. H. Guenther, M. R. Kozlowski, K. Lewis, and M. J. Soileau, eds., *Laser-Induced Damage in Optical Materials: 2000*, Proc. SPIE 4347 (2001).
G. J. Exarhos, A. H. Guenther, K. Lewis, M. J. Soileau, and C. J. Stolz eds., *Laser-Induced Damage in Optical Materials: 2001*, Proc. SPIE 4679 (2002).
G. J. Exarhos, A. H. Guenther, K. Lewis, N. Kaiser, M. J. Soileau, and C. J. Stolz eds., *Laser-Induced Damage in Optical Materials: 2002*, Proc. SPIE 4932 (2003).
G. J. Exarhos, A. H. Guenther, K. Lewis, N. Kaiser, M. J. Soileau, and C. J. Stolz eds., *Laser-Induced Damage in Optical Materials: 2003*, Proc. SPIE 5273 (2004).
G. J. Exarhos, A. H. Guenther, K. Lewis, N. Kaiser, M. J. Soileau, and C. J. Stolz eds., *Laser-Induced Damage in Optical Materials: 2004*, Proc. SPIE 5647 (2005).
G. J. Exarhos, A. H. Guenther, K. Lewis, D. Ristau, M. J. Soileau, and C. J. Stolz eds., *Laser-Induced Damage in Optical Materials: 2005*, Proc. SPIE 5991 (2006).

G. J. Exarhos, A. H. Guenther, K. Lewis, D. Ristau, M. J. Soileau, and C. J. Stolz eds., *Laser-Induced Damage in Optical Materials: 2006*, Proc. SPIE 6403 (2007).
G. J. Exarhos, D. Ristau, M. J. Soileau, and C. J. Stolz eds., *Laser-Induced Damage in Optical Materials: 2007*, Proc. SPIE 6720 (2008).

Compact Discs:

A. H. Guenther, ed., Laser-Induced Damage in Optical Materials: Collected papers 1969-1998 (a three CD-ROM set available from SPIE, P.O. Box 10, Bellingham, WA 98227-0010) (1999).
A. H. Guenther, ed., Laser-Induced Damage in Optical Materials: Collected papers 1999-2003 (CD-ROM available from SPIE, P.O. Box 10, Bellingham, WA 98227-0010) (2004).

Journal articles:

A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: A conference Report*, Appl. Opt. **13** (1): 74-88 (1974).
A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: 6th ASTM Symposium*, Appl. Opt. **14** (3): 698-715 (1975).
A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: 7th ASTM Symposium*, Appl. Opt. **15** (6): 1510-1529 (1976).
A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials:87th ASTM Symposium*, Appl. Opt. **16** (5): 1214-1231 (1977).
A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: 9th ASTM Symposium*, Appl. Opt. **17** (6): 2386-2411 (1978).
A. J. Glass and A. H. Guenther, eds., *Laser-Induced Damage in Optical Materials: 10th ASTM Symposium*, Appl. Opt. **18** (13): 2212-2229 (1979).
H. E. Bennett, A. J. Glass, A. H. Guenther, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 11th ASTM Symposium*, Appl. Opt. **19** (14): 2375-2397 (1980).
H. E. Bennett, A. J. Glass, A. H. Guenther, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 12th ASTM Symposium*, Appl. Opt. **20** (17): 3003-3019 (1981).
H. E. Bennett, A. H. Guenther, D. Milam, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 13th ASTM Symposium*, Appl. Opt. **22** (20): 3276-3296 (1983).
H. E. Bennett, A. H. Guenther, D. Milam, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 14th ASTM Symposium*, Appl. Opt. **23** (21): 3782-3795 (1984).
H. E. Bennett, A. H. Guenther, D. Milam, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 15th ASTM Symposium*, Appl. Opt. **25** (2): 258-275 (1986).
H. E. Bennett, A. H. Guenther, D. Milam, and B. E. Newnam, eds., *Laser-Induced Damage in Optical Materials: 16th ASTM Symposium*, Appl. Opt. **26** (5): 813-827 (1987).
A. H. Guenther, "Optics damage constrains laser design and performance," Laser Focus World, **29**, 83-87, 1992.
A. H. Guenther, "Previewing the Boulder Damage Symposium," Lasers and Optronics **12**, 25-26,1993.
A. H. Guenther, "Laser-Induced Damage in Optical Materials at the October 6-8, 1997 Symposium on Optical Materials for High-Power Lasers (Boulder Damage Symposium), Boulder, Colorado" J. Laser Appl. **9**, 261-266,1997.

Laser-Induced Damage in Thin-Film Optical Materials: 1970-2008

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ABSTRACT

The laser damage resistance of single- and multilayer thin-film coatings is generally the limiting factor on the power and energy output of high-power cw and pulsed lasers for all laser operating wavelengths from the vacuum-ultraviolet to the mid-infrared. For this reason coating deposition technology, thin-film materials properties, and laser damage tests have been prominent topics at every Boulder Damage Symposium (BDS) since 1971.

The ~500 papers concerning thin film properties and performance presented at these symposia during the past four decades have greatly advanced our understanding of laser-induced thin-film damage processes, parameter dependences, and selection and optimization of coating deposition technologies. This review features experimental results reported in the BDS Proceedings that illustrate ten important areas (selected by the author) in which major progress has resulted in coatings with high laser-induced damage thresholds in the environments of particular high-power lasers.

Keywords: coating deposition technologies, high-power laser optics, laser-induced-damage, thin films

SUMMARY

At the 1971 Boulder Damage Symposium (BDS), the third such meeting at the Boulder Laboratory of the National Bureau of Standards, Francis Turner[1] of Bausch & Lomb, Inc. presented the first report of experimental studies concerning the pulsed laser damage resistance of a variety of optical coatings. As the pioneering effort for what would follow during these last 37 years, Turner's study was a general survey of a number of single-layer coatings and quarter-wave stacks using a commercial ruby laser (694 nm) with a quite uncontrolled and spiking pulse format. Turner's primary finding was a general trend of higher damage thresholds for film materials with decreasing refractive index. At this same meeting, Austin and Guenther[2] reported their damage studies of a variety of antireflection (AR) coatings and attempted (unsuccessfully) to find a correlation with film stress. From that 1971 symposium to the present, thin film coatings have been one of the four major topical areas of these symposia. As a participant in nearly all of the past 38 Boulder Damage Symposia, I welcome the opportunity to consider what have been the most significant developments in thin film coatings for high-power lasers.

Fifteen years ago at the 1993 BDS, Pat Beauchamp[3] presented his perspective on what strategies had been effective in raising the laser damage thresholds (LIDT) of optical coatings. He cited three major means that had proven to yield large increases (pre-irradiation, porous AR coatings, and appropriate material selection) plus two others (overcoats and electric field profile shifting) that had yielded modest (~60%) increases. The present review made in 2008 also includes these five strategies, further optimized over the past 15 years, plus five more selected by this author that have yielded major progress. The list of ten includes:

1. Optical diagnostics for measuring ultra-low coating losses[6-8]

2. Development and optimization of superior coating deposition processes[9-15]

3. Identification and optimization of superior coating materials for particular lasers[7, 10]

4. Adoption of the "onset" protocol standard for LIDT measurements[16]

5. Identification and characterization of coating defects[17, 18]

6. Pre-irradiation protocols that produce substantial, permanent increases in LIDT[19-21]

7. Development of a functional LIDT for coated optics used in major laser facilities[21]

8. Coating design strategies that optimize standing-wave electric field profiles to increase LIDT[13, 22-24]

9. Beneficial applications of optical overcoatings[13, 21, 25, 26]

10. Application of multilayer dielectric reflectors on meter-scale diffraction gratings[27, 28]

The list was limited to ten topics to fit within the time constraints of the conference program. The author certainly aware that substantial progress also has been made in a number of other areas not included in the list, e.g. characterization and control of contamination, development of damage theory, identification of pulsewidth scaling dependences, and coating property measurements versus composition.

The illustrations that were shown in the oral presentation were nearly all derived from reports published in the proceedings of the Boulder Damage Symposia from 1971 to 2007. The reference citations below include the particular tables and figures used as illustrations. The interested reader should consult the original articles, either in the printed BDS proceedings published by the National Bureau of Standards (1969-1985), by the National Institute of Standards and Technology (1986-1989), and by the SPIE (1989-2007), or in the two CD-ROM sets of the BDS proceedings available from the SPIE, details of which are all listed in the 2007 Proceedings.[4] The SPIE Digital Library[5] also is a resource for the proceedings of the Boulder Damage Symposia from 1990 to 2007.

REFERENCES

[1] Turner, A.F., "Ruby laser damage thresholds in evaporated thin films and multilayer coatings," in *Damage in Laser Materials: 1971*, A.H. Guenther and A. J. Glass, eds., Natl. Bur. Stand. (U.S.) Spec. Publ. 356, 119-123 (1971).
[2] Austin, R.R. and Guenther, A.H., "An investigation of laser induced damage to four different single purpose anti-reflection coatings on fused silica substrates," in *Damage in Laser Materials: 1971*, pp. 137-152.
[3] Beauchamp, W.T. "Coping with the ever increasing demands of laser induced damage threshold requirements – a perspective" in *Laser-Induced Damage in Optical Materials: 1993*, H.E. Bennett, L.L. Chase, A.H. Guenther, B.E. Newnam, and M.J. Soileau, eds., Proc. SPIE Vol. 2114, 689-702 (1993).
[4] SPIE, *Laser-Induced Damage in Optical Materials: 2007,* G.J. Exarhos, A.H. Guenther, K.L. Lewis, D. Ristau, M.J. Soileau, and C.J. Stolz, eds., Proc. SPIE Vol. 6720, xxi-xxiii (2008).
[5] SPIE, *Laser-Induced Damage in Optical Materials*, SPIE Digital Library at:
http://spiedigitallibrary.aip.org/browse/vol_title.jsp?scode=L&start=4 .
[6] Jolin, L.J., Sanders, V.E. and Turner, T.P., "Cavity ringdown measurements of high-reflection mirrors at 1.06 μm," in *Laser Induced Damage in Optical Materials: 1988*, H.E. Bennett, A.H. Guenther, B.E. Newnam, and M.J. Soileau, eds., Natl. Inst. Stand. & Tech. Spec. Publ. 775, 166-174 (1989). Figure 1.
[7] Sanders, V.E., Early, J.W. and Leamon, W., "The response of multilayer dielectric coatings to low fluence ultraviolet light exposure," in *Laser Induced Damage in Optical Materials: 1989*, H.E. Bennett, L.L. Chase, A.H. Guenther, B.E. Newnam, and M.J. Soileau, eds., Natl. Inst. Stand. & Tech. Spec. Publ. 801 (SPIE Vol. 1438), 561-567 (1990). Figures 1 and 3.
[8] Markosyan, A., Route, R., Armandula, H. and Fejer, M., "PCI Technique for Thermal Absorption Measurements - Absorption Loss Measurements on LIGO Optics," presented at Workshop on Optical Coatings in Precision Measurements, Calif. Inst. Techn., Pasadena, CA, Mar. 20-21, 2008, www.ge.infn.it/%7Egemme/virgo/CoatingWorkshop/markosyan.pdf. Figure 10.
[9] Lalezari, R., "Review of ion beam sputtering," presented at Workshop on Optical Coatings in Precision Measurements, Calif. Inst. Techn., Pasadena, CA, Mar. 20-21, 2008. Figure 8.

www.ge.infn.it/%7Egemme/virgo/CoatingWorkshop/lalezari.html
[10] Route, R.K., Fejer, M.M., Alexandrovski, A. and Kondilenko, V., "Absorption Studies in Optical Coatings and Sapphire Crystals," Lasers and Optics Working Group LIGO LSC meeting, Hanford, WA, Aug. 8, 2002. Figure 8. http://www.ligo.caltech.edu/docs/G/G020374-00.pdf
[11] Shinn, M.D., Benson, S.V., Douglas, D., Evtushenko, P., Gould, C., Gubeli, J., Hardy, D., Jordan, K., Neil, G.R., Sexton, D.W. and Zhang, S., "Operation of the Jefferson Laboratory free-electron laser at high fluences," Abstract 6720-69 in *Laser-Induced Damage in Optical Materials: 2007.*
[12] Stewart, A.F. and Gallant, D.J., "Ultraviolet thin film characterization," in *Laser Induced Damage in Optical Materials: 1984*, H.E. Bennett, A.H. Guenther, D. Milam, and B.E. Newnam, eds., Natl. Bur. Stand. (U.S.) Spec. Publ. 727, 272-284 (1986). Figure 6.
[13] Stolz. C.J. and Taylor, J.R., "Damage threshold study of ion beam sputtered coatings for a visible high-repetition laser at LLNL," in *Laser-Induced Damage in Optical Materials: 1992*, H.E. Bennett, L.L. Chase, A.H. Guenther, B.E. Newnam, and M.J. Soileau, eds., Proc. SPIE Vol. 1848, 182-191 (1993). Tables 2, 5, and 7 and Fig. 1.
[14] Thomas, I.M., "Sol-gel coatings for high power laser optics - Past, Present and Future, in *Laser-Induced Damage in Optical Materials: 1993*, pp. 232-243. Figure 2.
[15] Beauchamp, W.T., in *Laser-Induced Damage in Optical Materials: 1993*, op. cit. Figure 4 from I.M. Thomas.
[16] Becker, J. and Bernhardt, A., "ISO 11254, an international standard for the determination of the laser induced damage threshold," in *Laser-Induced Damage in Optical Materials: 1993*, pp. 703-713. Figures 1 and 2.
[17] Stolz, C.J., Tench, R.J., Kozlowski, M.R. and Fornier, A., "A comparison of nodular defect seed geometries from different deposition techniques," in *Laser-Induced Damage in Optical Materials: 1995*, H.E. Bennett, A.H. Guenther, M.R. Kozlowski, B.E. Newnam, and M.J. Soileau, eds., Proc. SPIE Vol. 2714, 374-382 (1996). Figure 2.
[18] Genin, F.Y., Stolz, C.J. and Kozlowski, M.R., "Growth of laser-induced damage during repetitive illumination of HfO_2-SiO_2 multilayer mirror and polarizer coatings," in *Laser Induced Damage in Optical Materials: 1996*, H.E. Bennett, A.H. Guenther, M.R. Kozlowski, B.E. Newnam, and M.J. Soileau, eds., Proc. SPIE Vol. 2966, 273-282 (1996). Figures 3 and 10.
[19] Rainer, F., De Marco, F.P., Staggs, M.C., Kozlowski, M.R., Atherton, L.J. and Sheehan, L.M., "A historical perspective on fifteen years of laser damage thresholds at LLNL," in *Laser-Induced Damage in Optical Materials: 1993*, pp. 9-24. Figure 1.
[20] Wolfe, C.R., Kozlowski, M.R., Campbell, J.H., Rainer, F., Morgan, A.J. and Gonzales, R.P., "Laser conditioning of optical thin films," in *Laser Induced Damage in Optical Materials: 1989*, pp. 360-375. Figure 5.
[21] Stolz, C.J., Genin, F.Y., Reitter, T.A., Molau, N., Bevis, R.P., von Gunten, M.K., Smith, D.J. and Anzellotti, J.F., "Effect of SiO_2 overcoat thickness on laser damage morphology of HfO_2/SiO_2 Brewster's angle polarizers at 1064 nm," in *Laser Induced Damage in Optical Materials: 1996*, pp. 265-272. Figures 1 and 5 and Table 1.
[22] Newnam, B.E., Foltyn, S.R., Jolin, L.J. and Carniglia, C.K., "Multiple-shot ultraviolet laser damage resistance of nonquarterwave reflector designs for 248 nm," in *Laser Induced Damage in Optical Materials: 1981*, H.E. Bennett, A.H. Guenther, D. Milam, B.E. Newnam, and M.J. Soileau, eds., Natl. Bur. Stand. (U.S.) Spec. Publ. 799, 363-379 (1983). Figures 1 and 5.
[23] Gill, D.H., Newnam, B.E. and McLeod, J., "Use of non-quarter-wave designs to increase the damage resistance of reflectors at 532 and 1064 nanometers," in *Laser Induced Damage in Optical Materials: 1977*, A.J. Glass and A.H. Guenther, eds., Nat. Bur. Stand. (U.S.), Spec. Publ. 509, 260-270 (1978). Figures 1 and 3.
[24] Beauchamp, W.T., in *Laser-Induced Damage in Optical Materials: 1993*, op. cit. Figure 9 from C.K. Carniglia.
[25] Newnam, B.E., "Multifacet, metal mirror design for extreme-ultraviolet and soft x-ray free-electron laser resonators," in *Laser Induced Damage in Optical Materials: 1985*, H.E. Bennett, A.H. Guenther, D. Milam, and B.E. Newnam, eds., Natl. Bur. Stand. (U.S.) Spec. Publ. 746, 261-269 (1988). Figure 16.
[26] Kimura, W.D., Appert, Q.D., Arendt, P.N., Sanders, V.E. and Scott, W.L., "Tarnishing measurements of Al_2O_3 overcoated silver mirrors," in *Laser Induced Damage in Optical Materials: 1988*, pp. 267-272. Figures 3, 4, and 5.
[27] Nguyen, H.T., Britten, J.A., Carlson, T.C., Nissen, J.D., Summers, L.J., Hoaglan, C.R., Aasen, M.D., Peterson, J.E. and Jovanovic, I., "Gratings for high-energy petawatt lasers," in *Laser Induced Damage in Optical Materials: 2005*, G.J. Exarhos, A.H. Guenther, K.L. Lewis, D. Ristau, M.J. Soileau, and C.J. Stolz, eds., Proc. SPIE Vol. 5991, M-1 to M-8 (2005). Figure 4.
[28] Britten, J.A., Molander, W., Komashko, A.K. and Barty, C.P.J., "Multilayer dielectric gratings for petawatt-class laser systems," in *Laser Induced Damage in Optical Materials: 2003,* G.J. Exarhos, A.H. Guenther, N.B. Kaiser, K.L. Lewis, M.J. Soileau, and C.J. Stolz, eds., Proc. SPIE Vol. 5273, 1-7 (2004). Figure 3.

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[7132-12]

Questions and Answers

Q. I want to thank you for the publicity and I have two questions. Number 1 is, of the data you showed for the E-beam deposition versus ion beam deposition, were those single layers and the same substrate.

A. I don't know. All the data was on high reflectors. I didn't show single layers on my graphs.

Q. And the second question is, you made a statement that dual ion beam deposition or ion beam deposition is not good for pulsed lasers but ion beam deposition is better. What's the physics behind that?

A. Well, it hasn't realized as high a damage threshold and people have gone with what has worked for them, e-beam. There's curiosity about pulsed damage and ion beam coatings. Chris Stolz may be better able to comment on that. At LANL I hired Virgil Sanders specifically to assist me with laser fusion and free electron lasers using his ion beam technology. Except for mode-locked train in free electron lasers, essentially CW, there is very little energy in each micropulse. Ion beam coatings work wonderfully for that. The worst possible world for laser coatings is nanosecond pulses at high repetition rate. That is the most difficult scenario, much more difficult than picosecond pulses coming along with the same average power.

A. It's been my experience that different deposition technologies lend themselves to different pulse lengths and repetition frequencies. Ion beam coatings seem to do very well at very short pulses and as you go to regions of high absorption. The issue in terms of damage issues at the nanosecond pulse range is that these defects are popping out, and if they can't do that in a gentle and benign way, then what's left behind grows very rapidly. So the e-beam coatings are so much more fragile that when the defects pop out, it's a benign ejection and the dense films are so much more adhesive that failure is a lot more catastrophic.

A. With the e-beam, since the stress in the film is so much lower, again when you're in a pulsed environment and the defect ejects, it doesn't tear the film apart. But I would agree that for the FEL's the IBS coatings work so much better and also they're more stable because you put them in vacuum, they don't shift on you compared with the e-beam.

A. I believe that the lowest order of damage in a free electron laser is not catastrophic damage, rather its thermal distortion of the optics.