The fundamental mechanism of laser-induced damage in optical components for ultrashort-pulse laser systems

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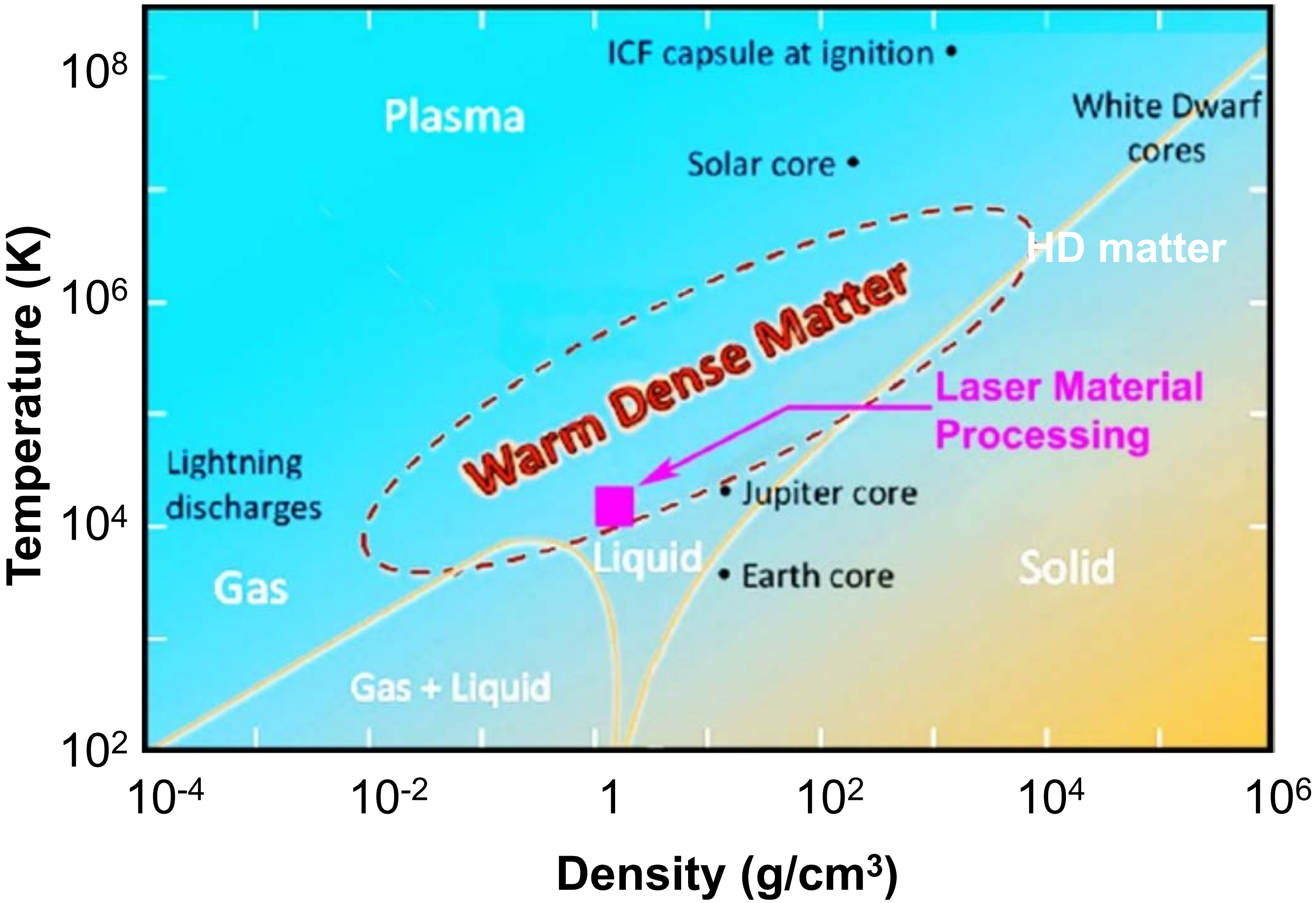
Summary

Basic concepts on the mechanisms and management of laser induced damage in short-pulse lasers systems are discussed

- Two principle mechanisms are responsible for facilitating damage initiation:
  - absorption by defects
  - the presence of contamination
- Laser induced damage thresholds must be considered as a function of:
  - single pulses
  - multiple pulses
  - damage growth
- Achieving and maintaining high damage performance requires the optimization of:
  - optical designs (including selection of material and manufacturing method)
  - control of contamination issues
  - management of damage growth

Laser-induced damage is governed by the excitation of the material to Warm Dense Matter state and its subsequent relaxation response

- **Laser damage can be described in terms of three main mechanisms:**
  - ○ **Defect-driven energy coupling (strongly dependent on laser parameters)**
  - ○ **Excitation leading to plasma formation**
  - ○ **Relaxation of superheated material (strongly dependent on material properties)**



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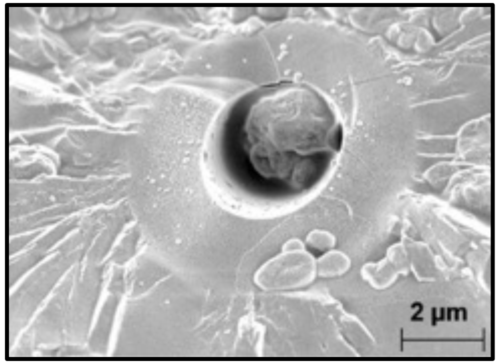
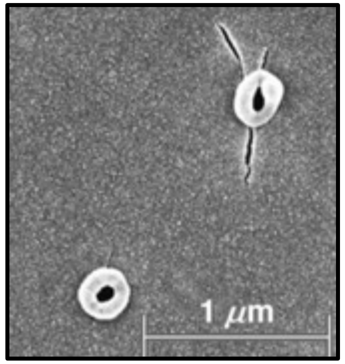
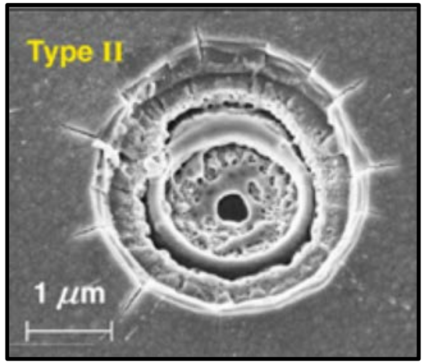
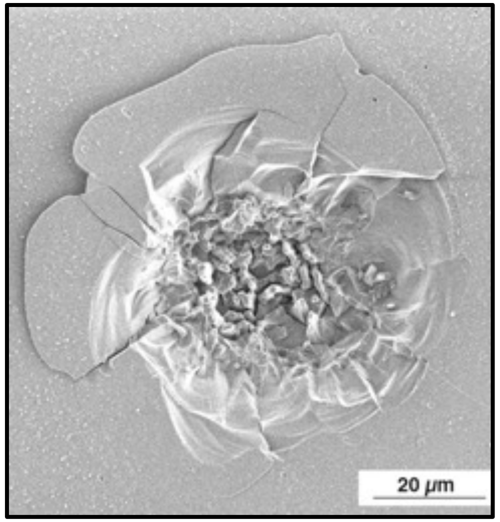
  - **Excitation leading to plasma formation**
  - **Relaxation of superheated material (strongly dependent on material properties)**

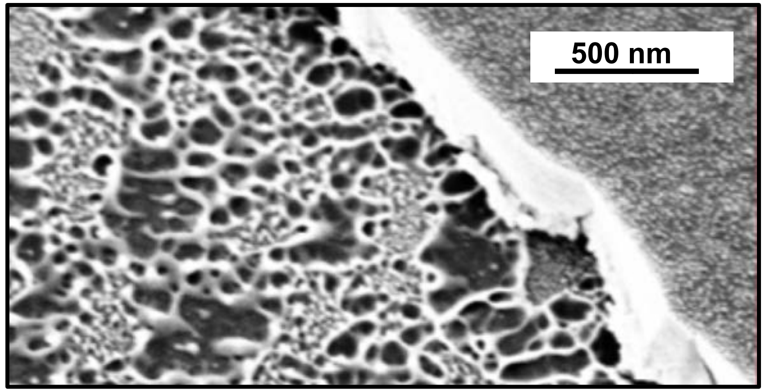
- **The damage site morphology is associated with transient pressures of the order of**
  - **10 GPa under ns irradiation and**
  - **100 GPa under fs irradiation**











Damage in ultrashort-pulse laser systems (pulses < 10 ps) is typically concerns reflective optical components

Three general types of reflective components (e.g., mirrors and gratings) are used:

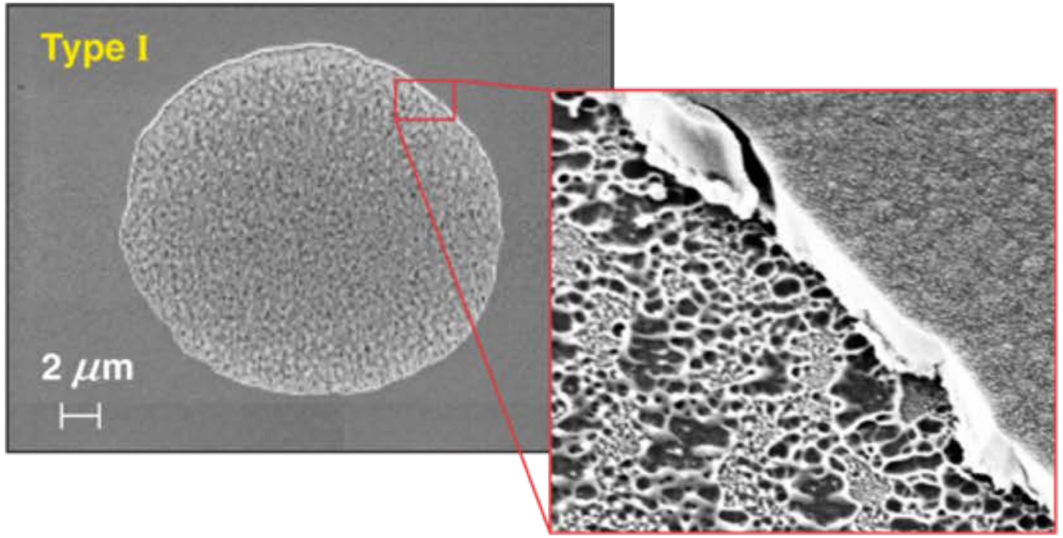
- ☐ **Multilayer dielectric (MLD)**
  - ○ composed of multiple thin layers of alternating higher- and lower-refractive-index dielectric materials
  - ○ Exhibit highest damage threshold

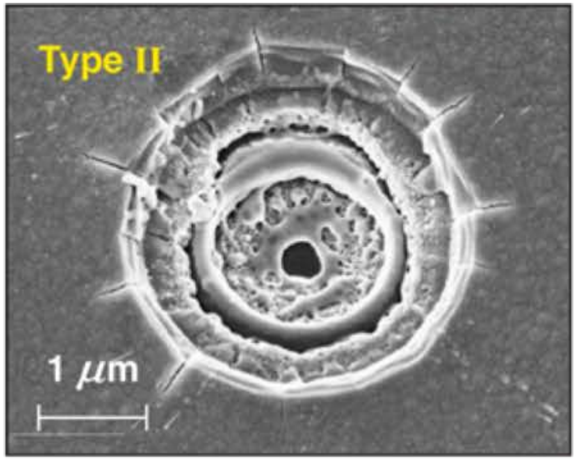
- ☐ **Metal coated**
  - ○ Broadband response with the lowest dispersion
  - ○ Exhibit lower reflectivity and lower damage threshold

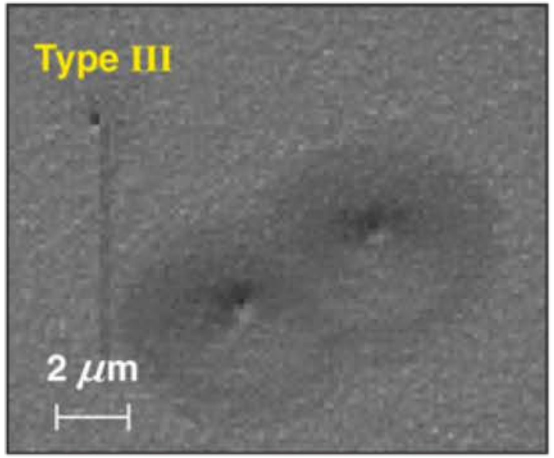
- ☐ **Hybrid**
  - ○ metal coating supplemented by a few layers of dielectric material
  - ○ Exhibit higher reflectivity and damage performance

This presentation is focused on the higher damage-threshold designs involving layers of dielectric materials on the outer surface.

There are distinct damage-initiation mechanisms and associated damage morphologies in nodule-free SiO_2/HfO_2 MLD mirrors







A. A. Kozlov *et al.*, Sci. Rep. 9, 607 (2019).

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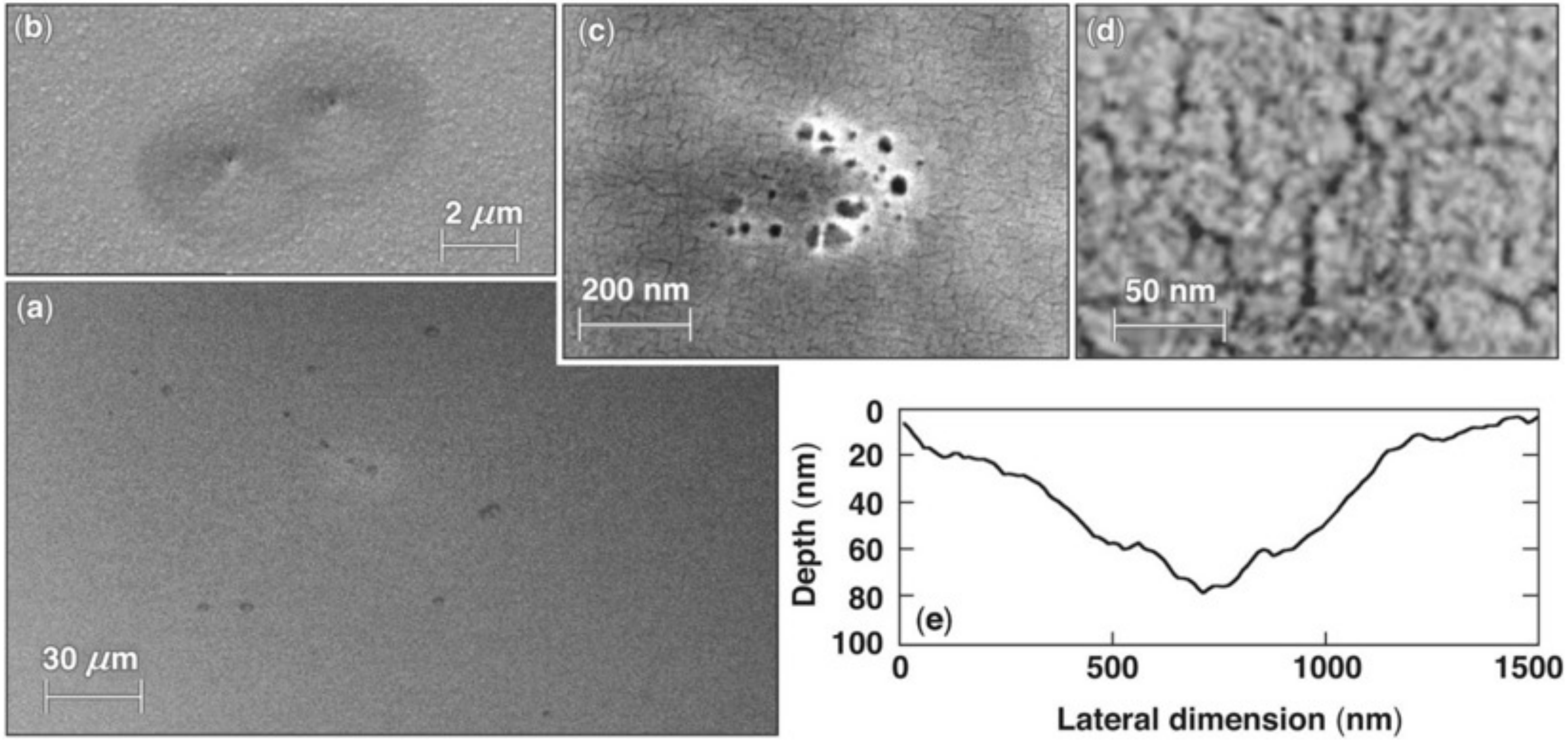
- Occurs with pulses $< \approx 2.5$ ps
- Damage driven by electric-field intensity (EFI) distribution
- Volume breakdown leads to pressure-induced removal of overlaying material
- Remnant melted material in the crater with fractured walls

- Occur with pulses $> \approx 2.5$ ps
- Damage driven by isolated defects located:
  - Type II: near electric-field intensity peaks
  - Type III: <150 nm from the surface of the top layer
- Morphology indicative of localized melting and boiling

- Damage for pulses shorter than ≈2 ps corresponds to peak-intensity regions of the beam profile, driven by the electric field and nearly uniformly distributed material defects.

Type-III damage is entirely confined to the top layer

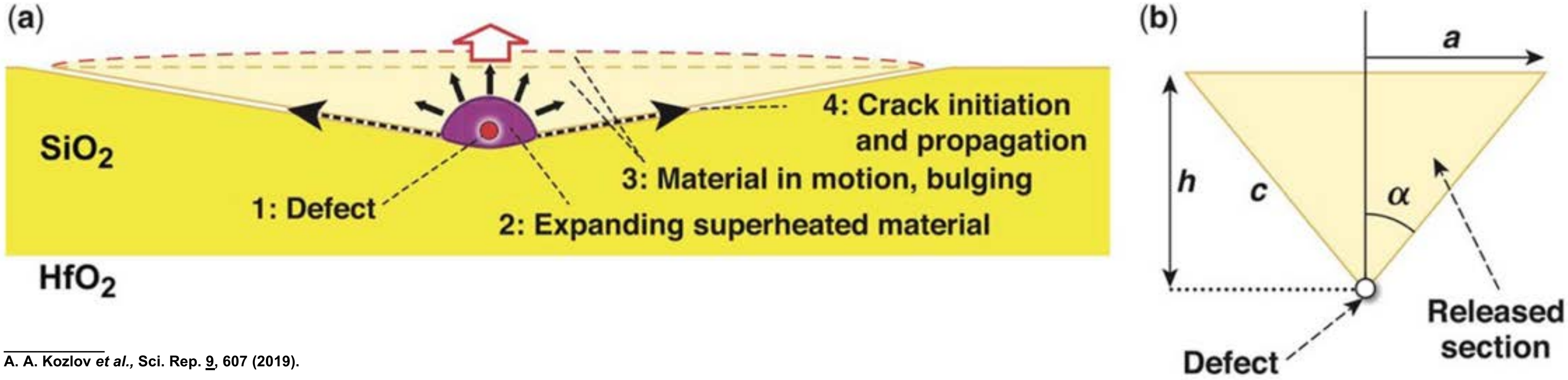
Type-III damage sites in SiO_2 under exposure to 1064-nm pulses



A. A. Kozlov *et al.*, Sci. Rep. 9, 607 (2019).

- Conical craters have depths <150 nm with a quasi-spherical void typically present at the bottom of the craters, possibly the result of the superheated defect
- There is no correlation with the local EFI peak

Depiction of the mechanism for type-III damage

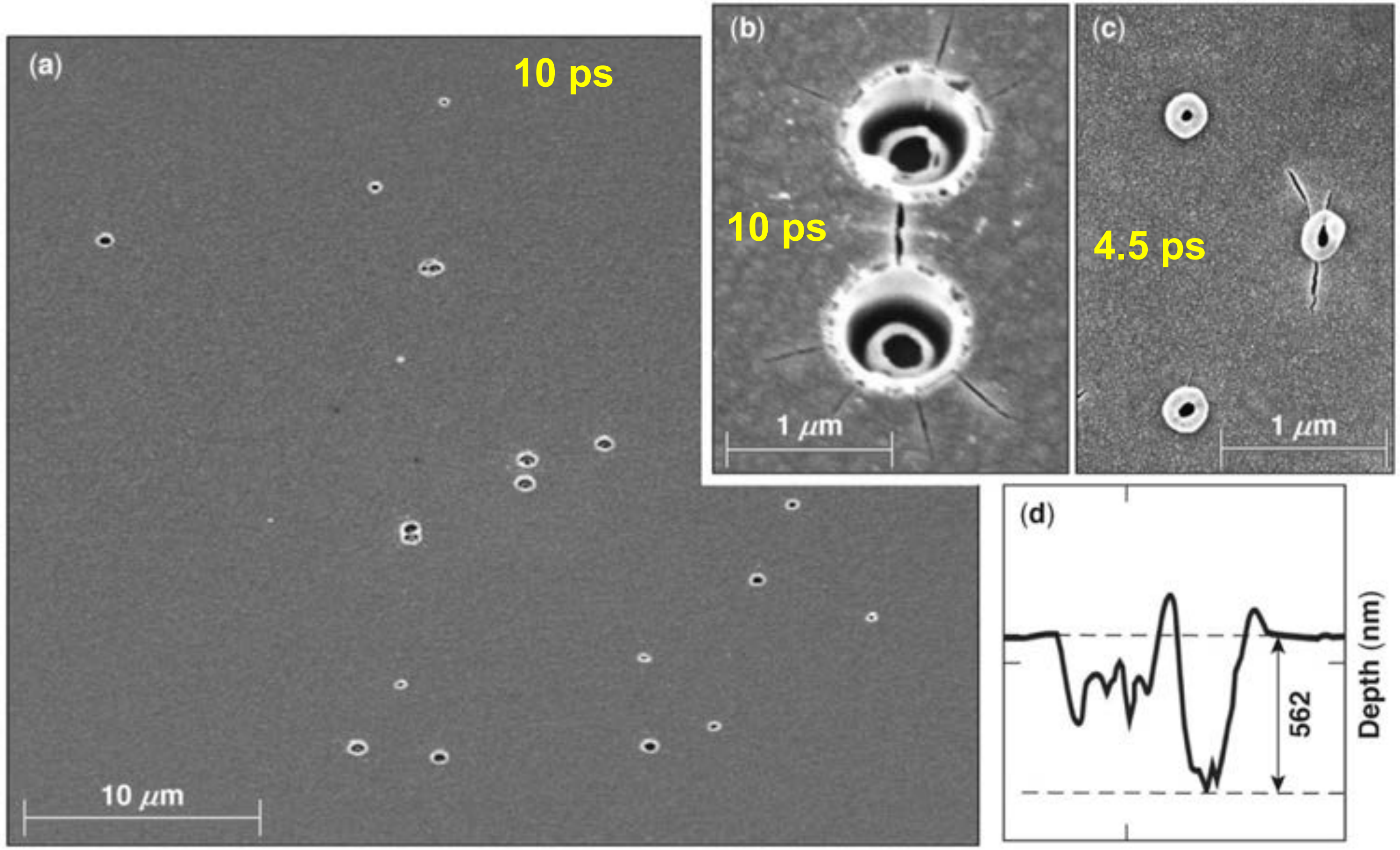


A. A. Kozlov *et al.*, Sci. Rep. 9, 607 (2019).

- Pressure-driven material ejection is initiated by isolated defects
- The pressure generated is sufficient to remove material above the defect only for shallow defects
- We anticipate that deeper defects create small voids containing melted material

Type-II damage morphology in SiO_2/HfO_2 coating points to localized defect-driven damage by subsurface explosions

Type-II damage sites under exposure to 1064-nm pulses



- Damage sites are isolated, indicating that they originate from defects
- The presence of melted material and a vent hole indicates the presence of melted and gaseous material involved
- Complex crater morphology contains a venting hole and one or more inner quasi-spherical shells, indicating multiple layers are involved
- Location of damage initiation corresponds to the local EFI peak
- Difference in thermomechanical properties of layer materials contribute to the damage morphology

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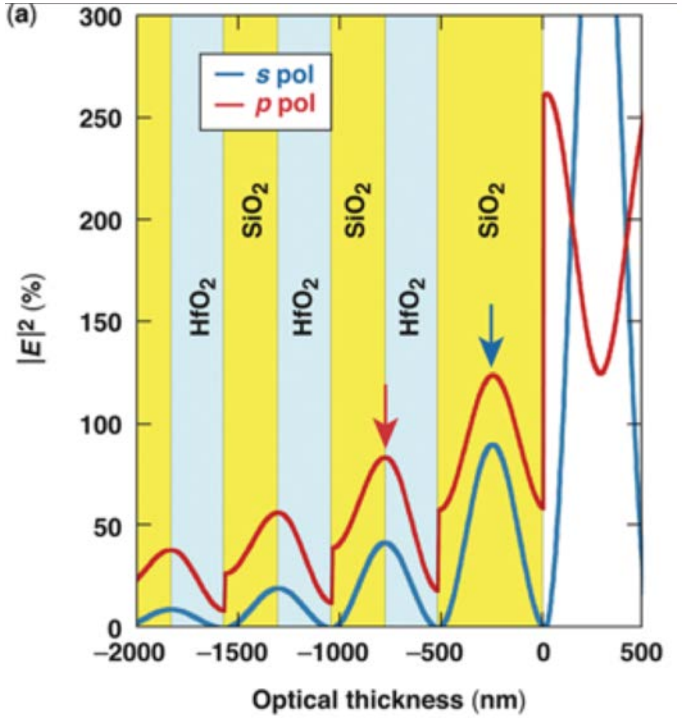
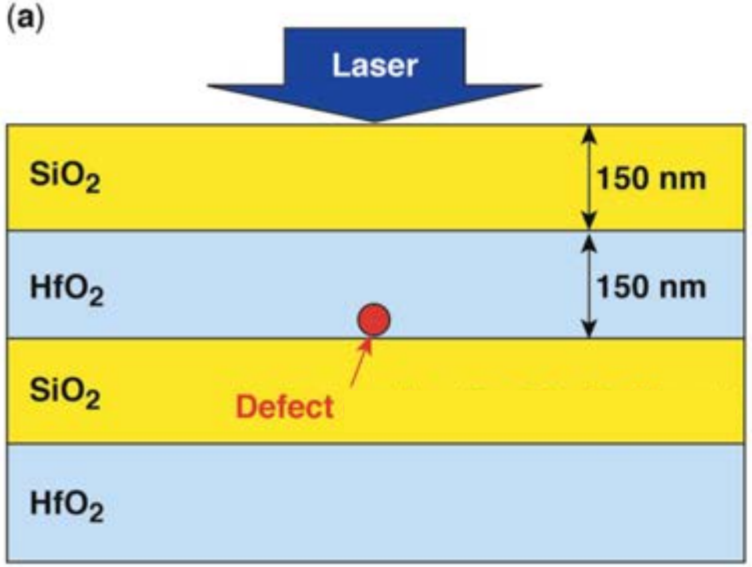
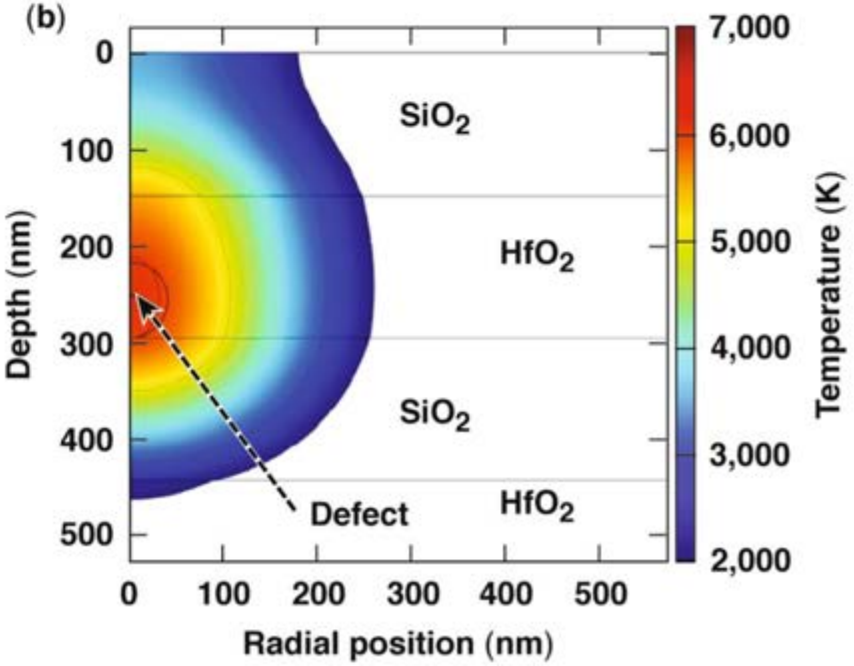
A. A. Kozlov *et al.*, Sci. Rep. 9, 607 (2019).

Depiction of the crater formation mechanism for type-II damage



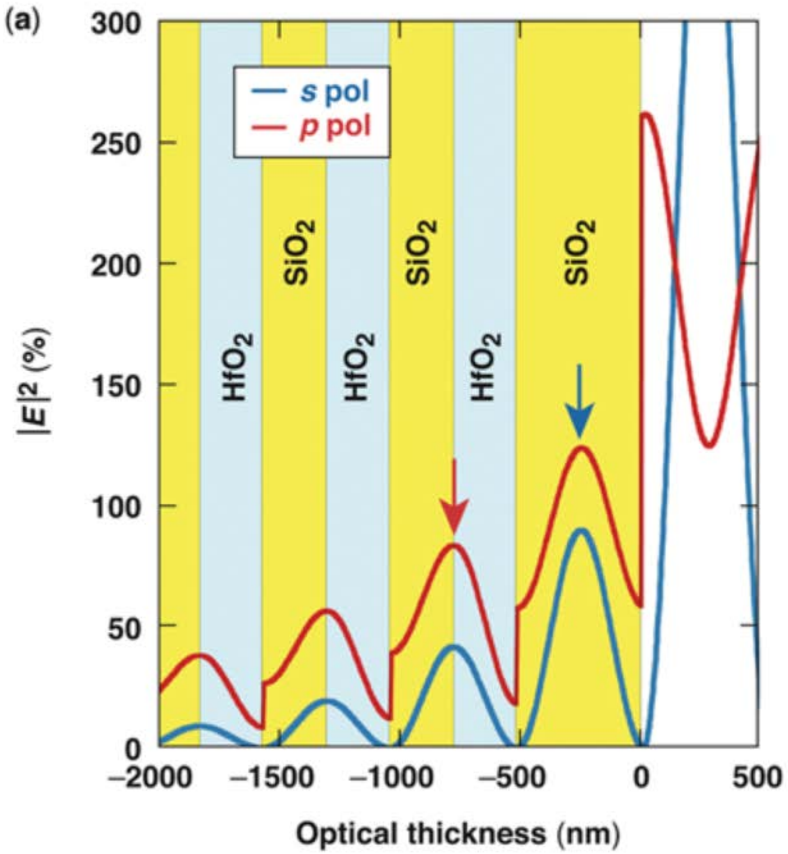


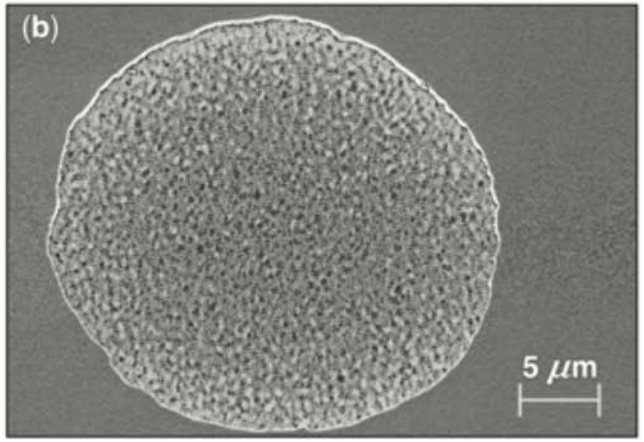


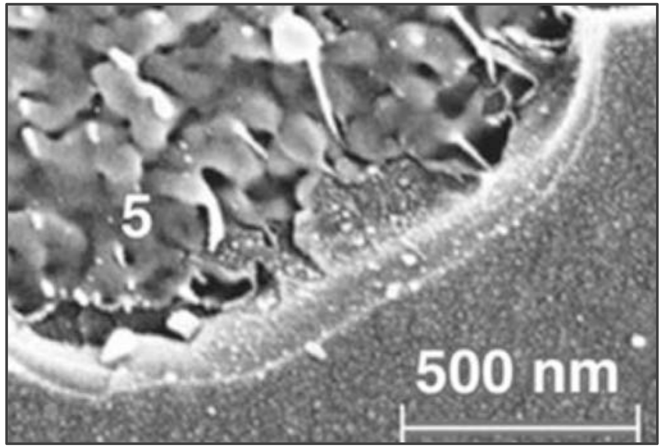
- **Defect structures (diameter on the order of 50 nm) located deeper in the structure absorb significant amounts of energy at peak electric-field locations, leading to localized superheating**
- **The initial pressure generated cannot support fracture of the layer above**
- **However, heat diffusion leads to softening of the top layer, allowing formation of a venting path**

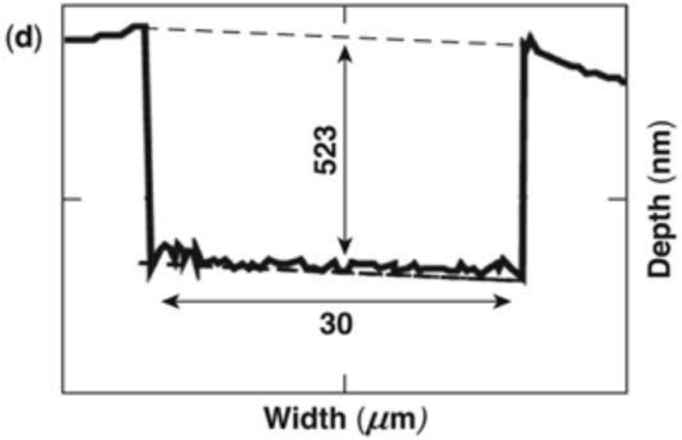
Type-I damage in SiO_2/HfO_2 coatings suggests explosive boiling in the areas of local electric-field intensification

Type-I damage sites under exposure to 1064-nm pulses





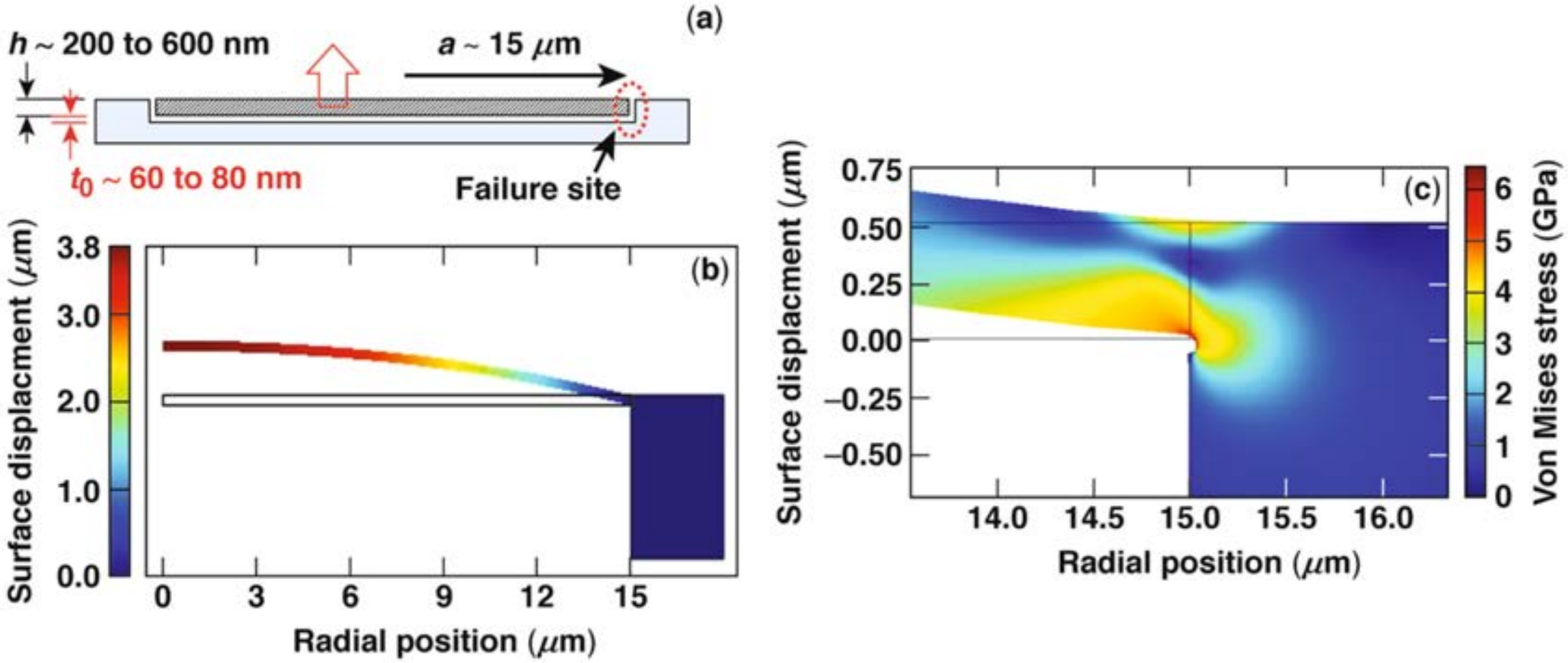




- The base of the craters shows remnants of an explosive boiling process accompanied by molten material ejection
- Damage crater depth coincides with the local EFI peak

A. A. Kozlov *et al.*, Sci. Rep. 9, 607 (2019).

Depiction of the mechanism for the formation of type-I damage

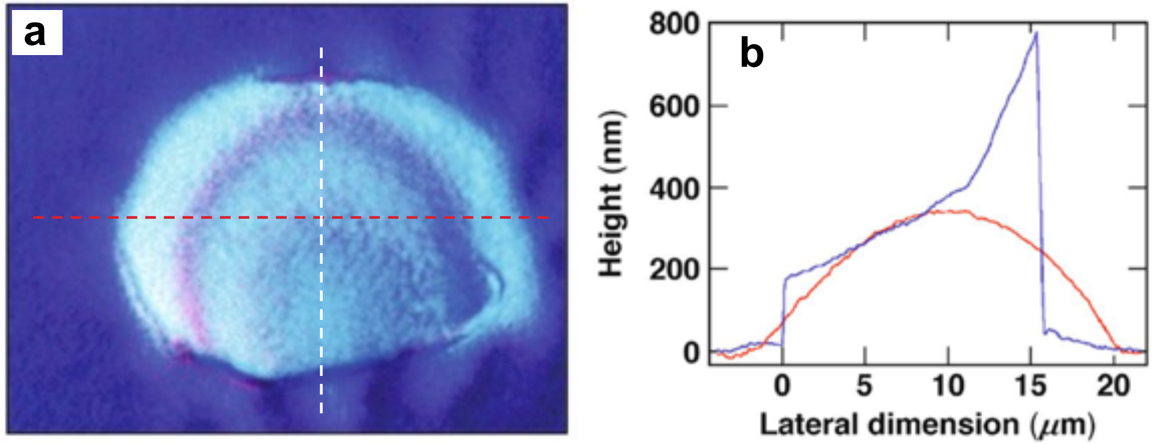


- Plasma is formed in a volume of ~15-μm radius and 60 to 80 nm thick, determined by 3-D EFI distribution
- The pressure energy is sufficient to support shear fracture and ejection of the top layer
- Rapid cooling results in limited remnants of liquid material

The morphology of type-I damage sites is governed by the laser pulse parameters

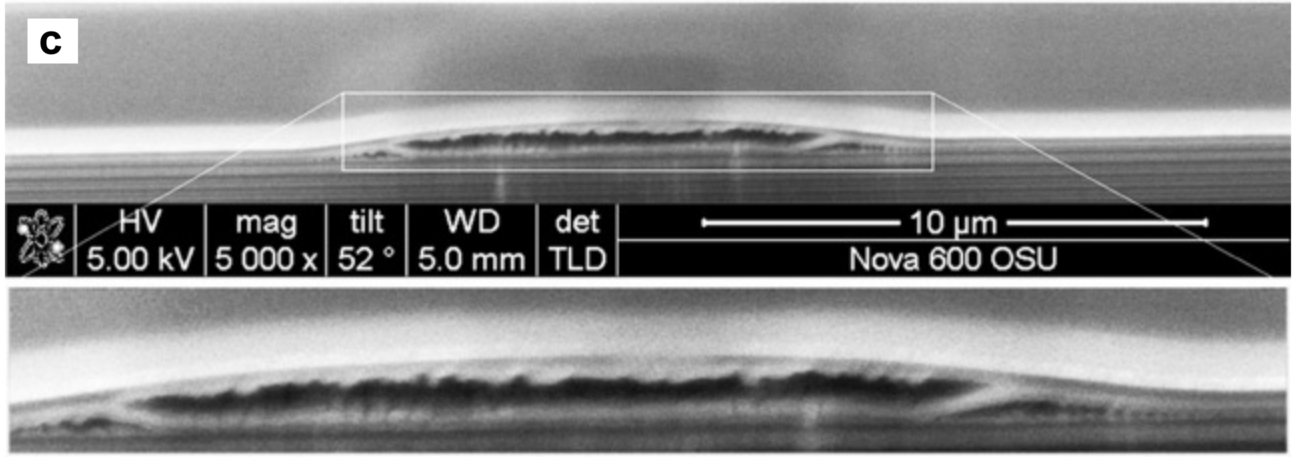
- Damage morphology on MLD optics with fs pulses involves transient formation of blisters
- The "eruption" of the blister depends on the excess energy deposited during the laser pulse, which generally decreases with decreasing pulse duration

Damage site generated with a 600-fs pulse



A. A. Kozlov *et al.*, Sci. Rep. 9, 607 (2019).

Damage site generated with a 10-fs pulse

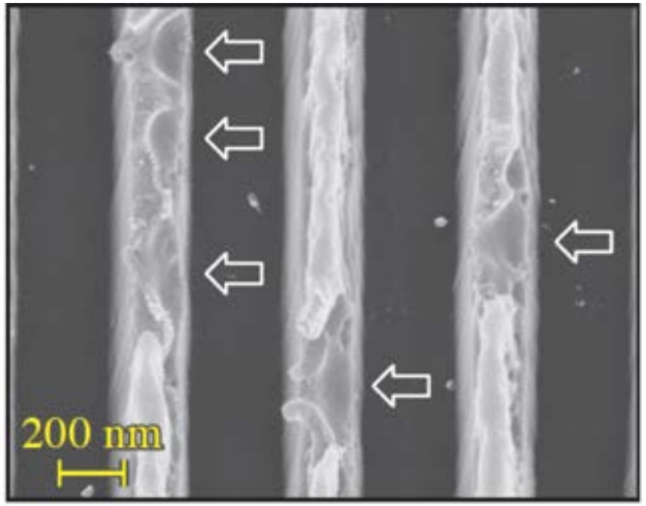


K. Kafka, PhD Thesis (2016)

- Damage may be "hidden" inside the coating layers (the damage process was initiated but there was not enough excess energy to cause observable morphological changes)

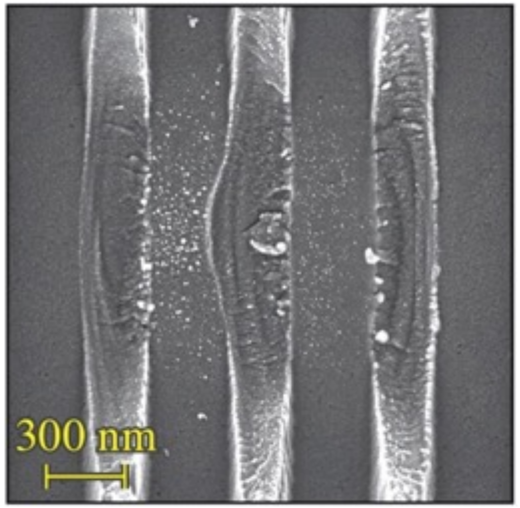
The damage-initiation mechanisms in SiO_2/HfO_2 MLD gratings are analogous to those observed in MLD mirrors

Damage with 600-fs pulses



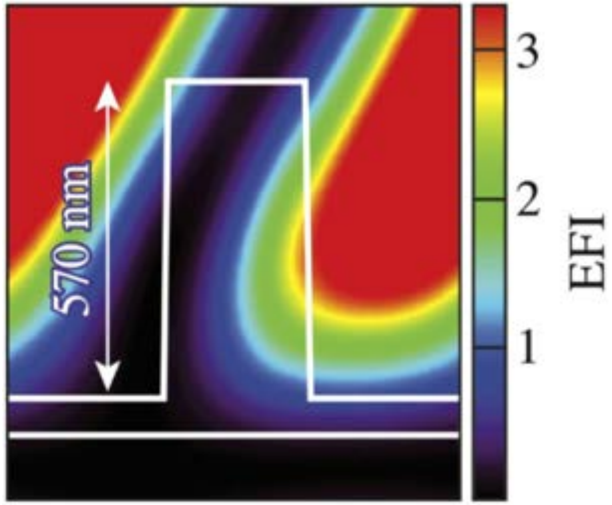
Type I damage

Damage with 10-ps pulses



Type II damage

Electric-field distribution

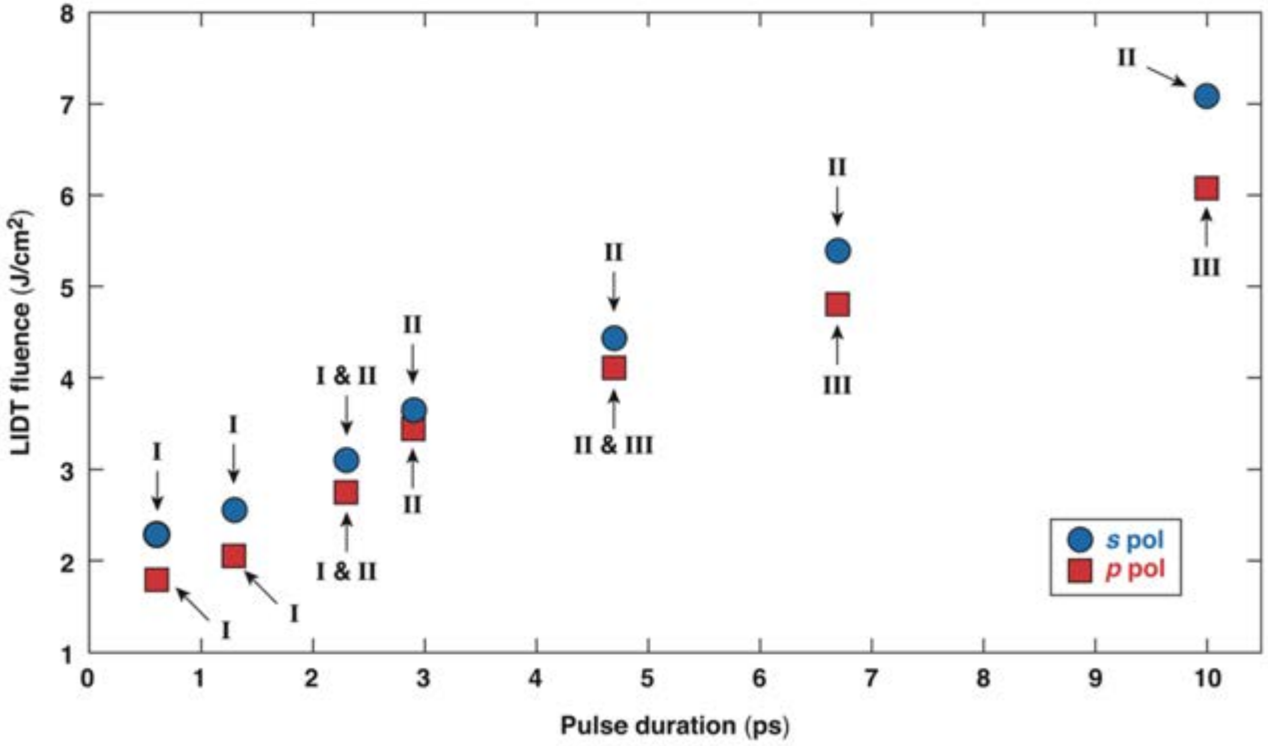


B. Hoffman *et al.*, Optics Express.28, 24928 (2020).

- Damage in MLD gratings is initiated in the pillars driven by local electric-field intensity and involves mechanisms identical to those observed in MLD mirrors:
  - for pulses <2 ps, removal of silica pillar sections involving volume breakdown
  - for pulses >3 ps, removal of sections of one or more adjacent pillars induced by energy deposition within a defect structure (diameter on the order of 50 nm) inside a pillar

Damage can be initiated from different defect structures on the same optic depending on excitation parameters

Damage threshold versus pulse duration for the same MLD optic



The damage morphology type (I, II, or III) formed at the laser-induced damage threshold fluence is observed to vary as a function of pulse duration and polarization

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A. A. Kozlov *et al.*, Sci. Rep. 9, 607 (2019).

- This behavior can be justified assuming that there are three damage-initiation mechanisms that can theoretically be represented by three damage-threshold profiles
- For each pulse length, damage initiation is governed by the mechanism that presents the lowest LIDT

Damage initiation involves a sequence of distinct phases spanning much longer than the pulse duration

Phase 1: Excitation during the laser pulse

a. Initiation of electronic excitation :	Energy from the laser pulse is coupled to a localized material volume (facilitated by defects)
b. Generation of plasma:	Near solid-state-density conduction band electron population is generated that can reach critical plasma density
c. Energy deposition on material:	The energy coupling from the laser beam is greatly enhanced following plasma generation

Phase 2: Heating of the lattice during and after the laser pulse (1-ps to 100-ps time scale)

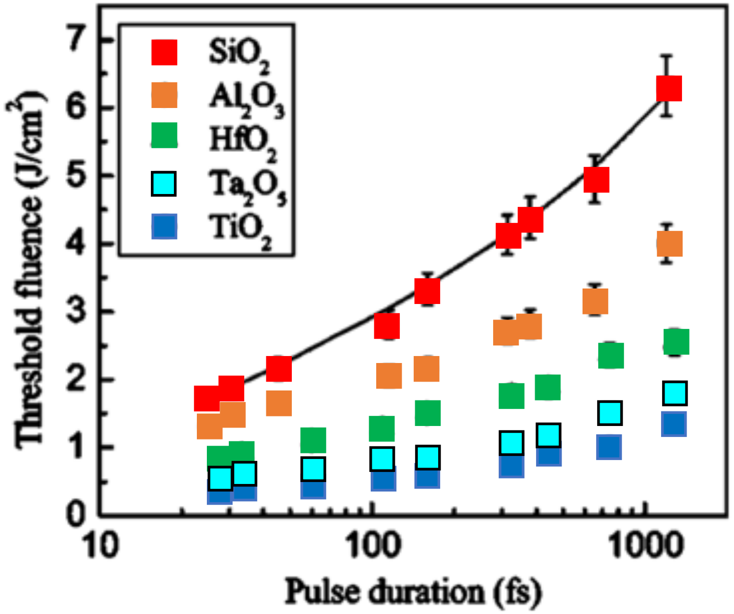
a. Electronic relaxation:	The excited electrons relax into the ground state and the energy is transferred into the lattice (phonons/heat)
b. Phase transition:	Melting but most often superheating of the affected material volume initiates the damage site formation process

Phase 3: Material relaxation, formation of the damage sites (1-ns to 100-ns time scale)

a. Energy partitioning:	Stored energy is released via pressure (shock) wave, heat diffusion, radiative emission, and energy needed to generate the final damage site morphology (material ejection, layer removal, cracking etc.)
b. Formation of the damage site:	Material flow and ejection driven by high temperature, pressure, and stresses

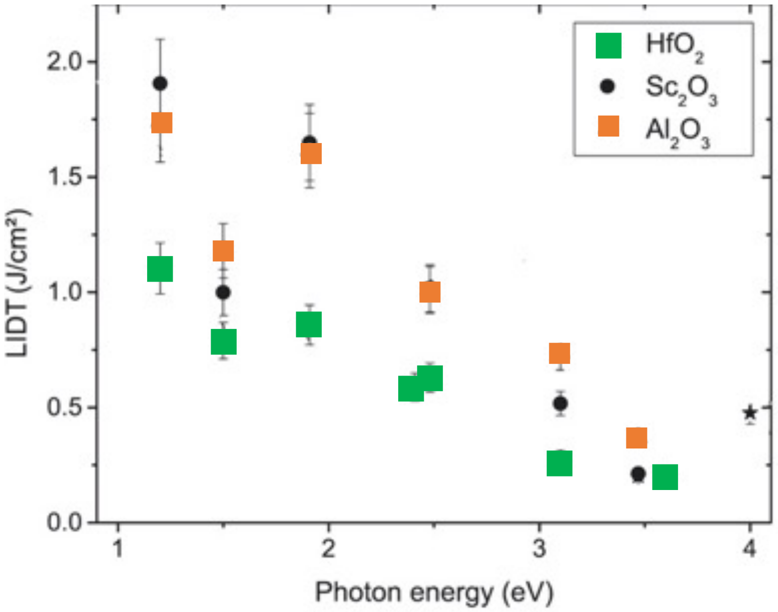
The damage threshold depends on the laser wavelength and pulse duration and material electronic properties

LIDT versus Pulse length



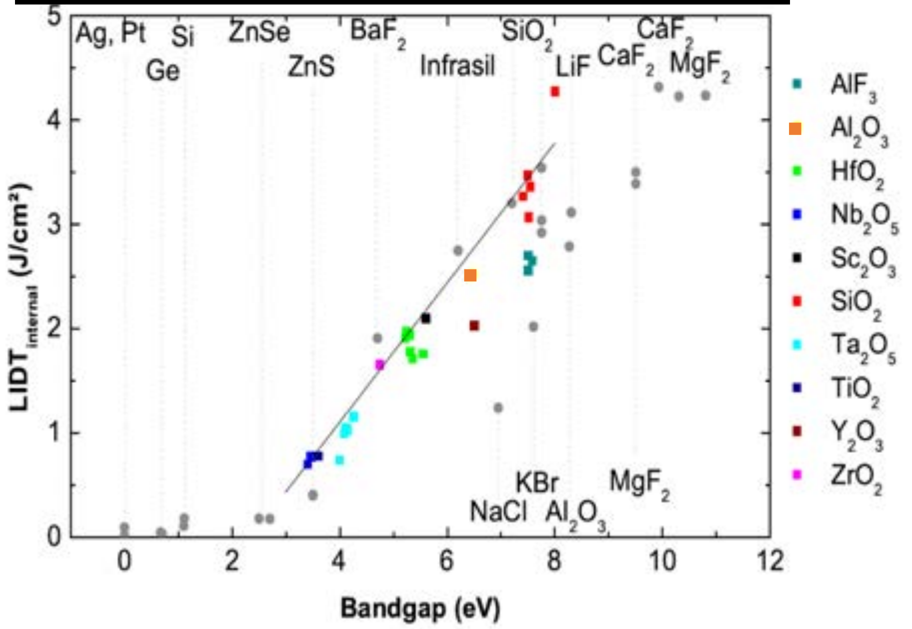
Mero et al., Phys. Rev. B 71, 115109 (2005).

LIDT versus Wavelength



L Gallais et al., J. Appl. Phys. 117, 223103 (2015).

LIDT versus Band gap



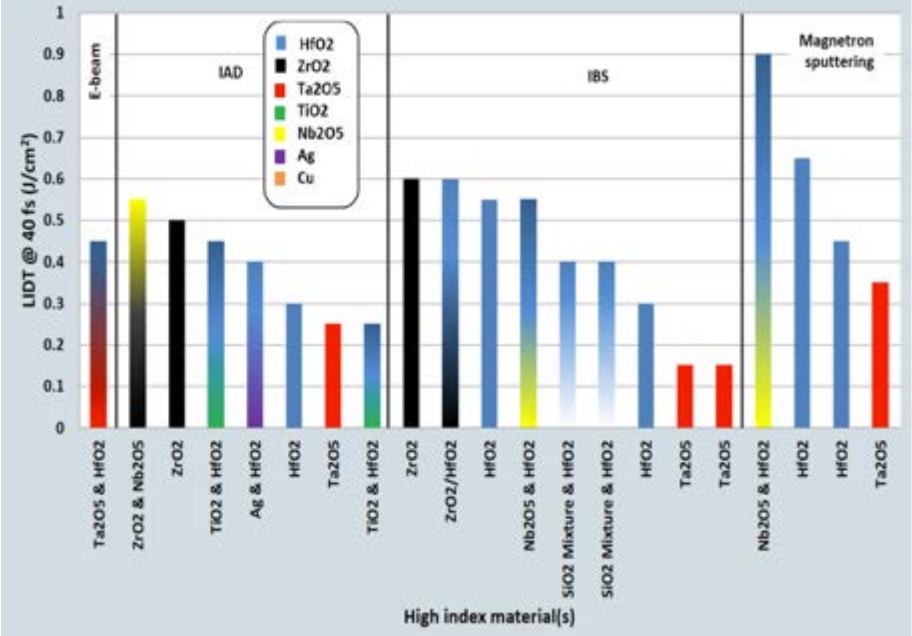
L Gallais et al., Appl. Opt. 53, A186 (2014).

- The damage threshold exhibits a weak dependence on the beam intensity
  - damage requires energy; therefore laser fluence is an important parameter
- The damage threshold exhibits a strong dependence on the photon energy and material band gap
  - nonlinear excitation (multiphoton absorption) involved in the excitation

Considerations to select optics for ultrashort-pulse laser systems

- **Utilize knowledge regarding the general design parameters of MLD optics for use under different operational parameters (e.g., laser-damage competition)**
- **Use a high-quality damage-testing facility to evaluate:**
  - **Single-pulse damage threshold**
  - **Multi-pulse damage threshold**
  - **Damage growth (catastrophic damage) threshold**
- **Understand the origin of the damage (defects in the manufactured material, contamination during handling or from the operational environment, secondary contamination from stray beams, etc.)**

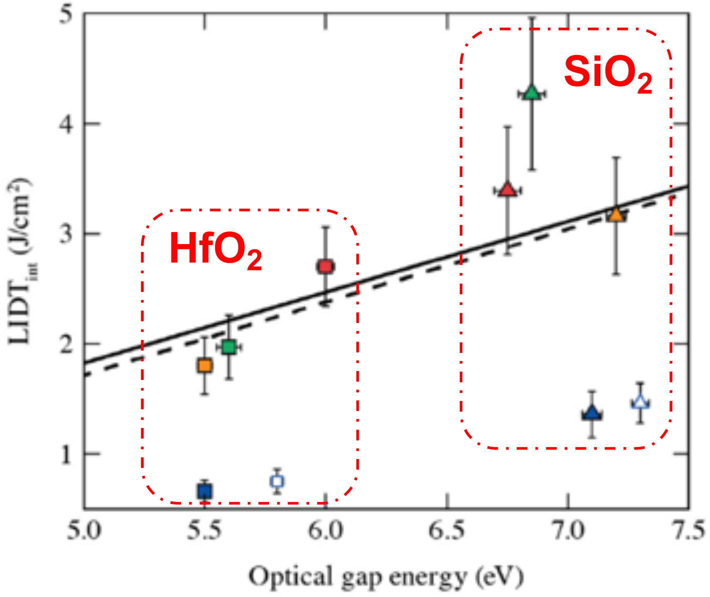
Results of the Laser Damage Conference 2016
HR broadband mirror damage competition



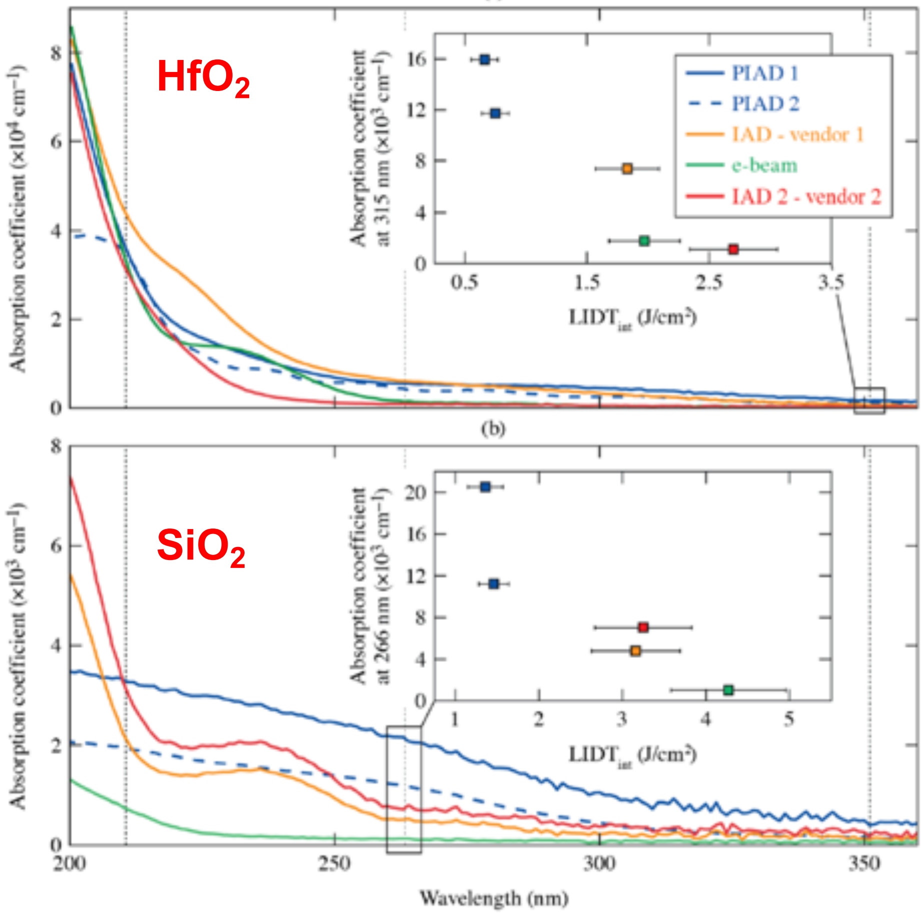
R. A.. Negres et al., Proc. of SPIE Vol. 10014, 100140E-1 *(2016).*

Defects are the catalyst in damage initiation, making damage performance strongly dependent on the manufacturing process

- **Nominally identical materials exhibit different LIDT's and absorption edge profiles**
- **These differences originate in the manufacturing process via variations in**
    - **material structure and**
    - **defect content**



LIDT vs absorption edge characteristics



M. Chorel et al., Optics Express 27, 16922 (2019).

- **Results indicate that the damage threshold is directly related to the absorptivity (supported by defects) at multiples of the operational wavelength**
- **This indicates the important role of defects in the nonlinear excitation involved in damage initiation**

Repeated exposure typically leads to reduction of the LIDT or damage growth

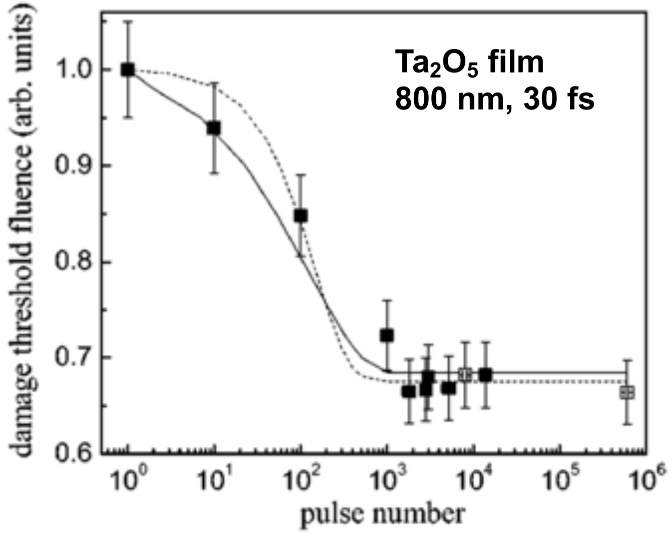
a) Incubation effects:

- Sub-damage fluence excitation can lead to defect generation, resulting in lowering the LIDT
- This "incubation" effect is commonly observed with shorter pulses and excitation wavelengths

b) Damage growth:

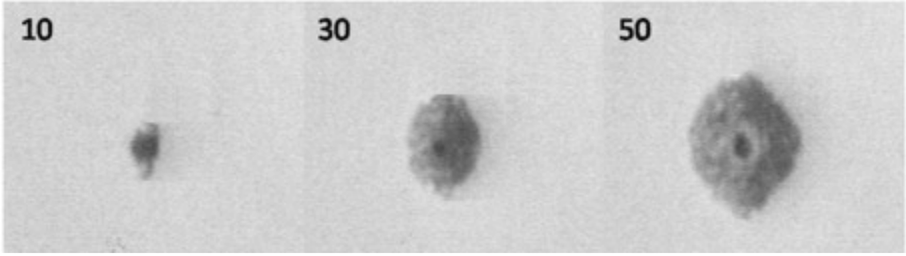
- Small damage initiation sites may be stable (do not grow) under subsequent exposure at same fluence
- In this case, the "damage-growth threshold" is defined as the fluence at the onset of damage growth
- The damage-growth threshold is the most important parameter in large-aperture laser systems where limited damage may be introduced at low fluences

LIDT versus number of pulses



Mero et al., Optical Engineering 44, 051107 (2005).

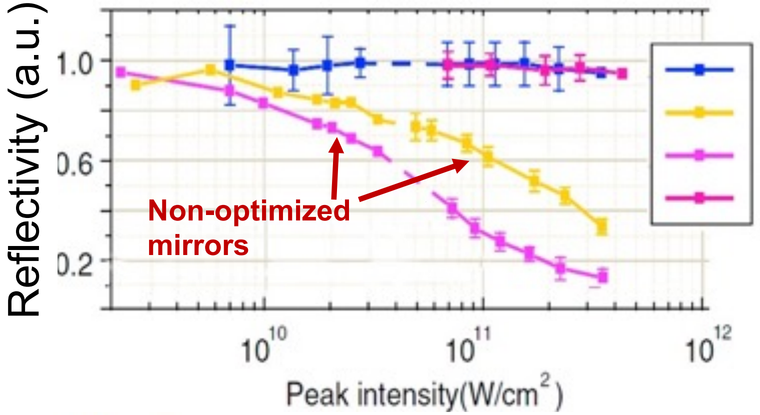
Damage site size versus number of pulses

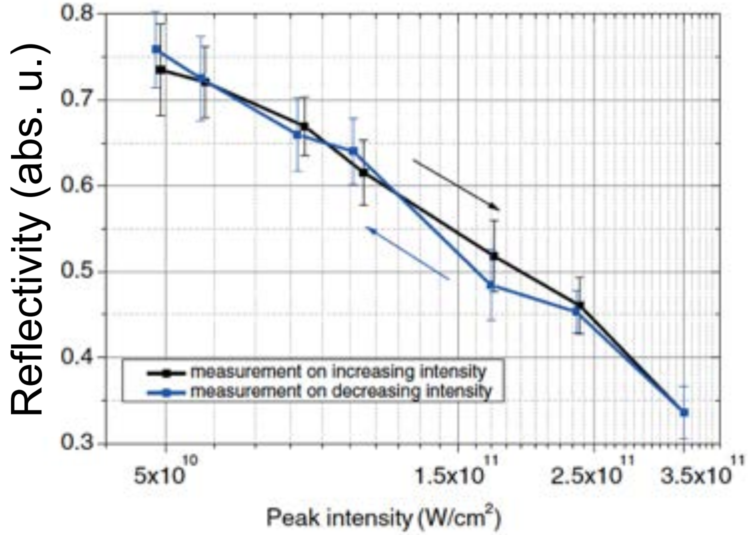


Optics exposed to few-cycle, ≈10^{13} W/cm^2 pulses can undergo transient changes in optical performance

- **Nonlinear processes can introduce transient but reversible changes in the index of refraction**
- **The properties of the MLD materials at peak intensities must be incorporated in the design of the optical elements (to minimize or utilize)**
- **The damage threshold definition may be expanded to include functional failure, which may occur without the presence of physical (classical) damage**

Reflectivity vs Laser intensity





For a series of MLD mirrors
(exposure to 400-nm, 40-fs pulses)

Razskazovskaya *et al.*, Optica 9, 803 (2015)

Contamination and laser-induced surface modifications in vacuum are well recognized problems

1) Deposition of organics during manufacturing or contaminated operational environment
   - Residual organics deposited on gratings during manufacturing [H. P. Howard *et al*., Appl. Opt. 52(8), 1682 (2013)]
   - Accidental oil contamination of gratings [T. Jitsuno *et al*., Proc. SPIE 8786, 87860B (2013)]

2) Laser-induced photochemical reactions on the surface of optical materials exposed to vacuum environment (UV and short-pulse applications)
   - Deposition of an organic layer in the presence of volatile materials [B. R. Muller *et al*., Rev. Sci. Instrument 63, 1428 (1992)]
   - Material removal/etching, defect formation [A. Burnham *et al*., Proc. SPIE 4134, 243, (2000)]

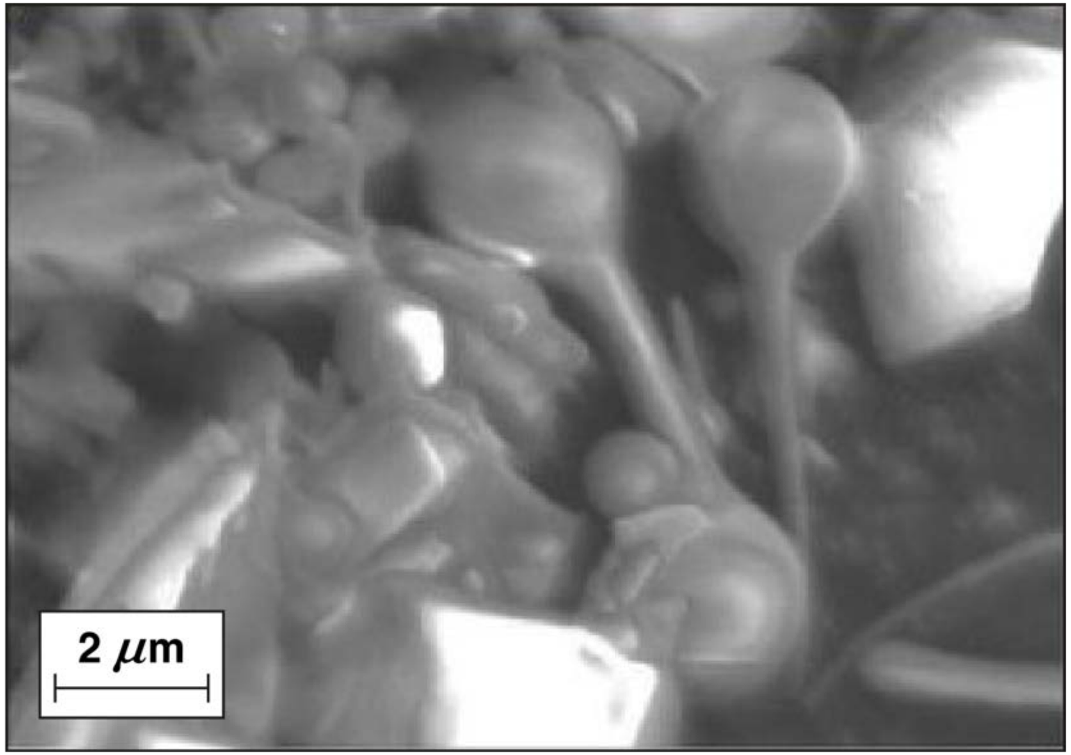
3) Deposition of particles, nanoscale and microscale in diameter

Contamination particles located on the surface of reflective optics in short-pulse systems are a major concern

Contamination particles found on laser optical components are generated from

1) Handling
    - typically fragments of material used in packaging and mounting
2) Debris generated in the operational environment by laser damage on optics and ablation of surrounding structures by stray beams
    - ejected material in vacuum following laser ablation/damage. Surface tension promotes quasi spherical shapes
    - mechanical fractured having quasi planar surfaces and areas of different curvatures
3) Debris from mounting structures and connected target chambers

SEM images of particles collected on the exit surface of a GDS optic in NIF



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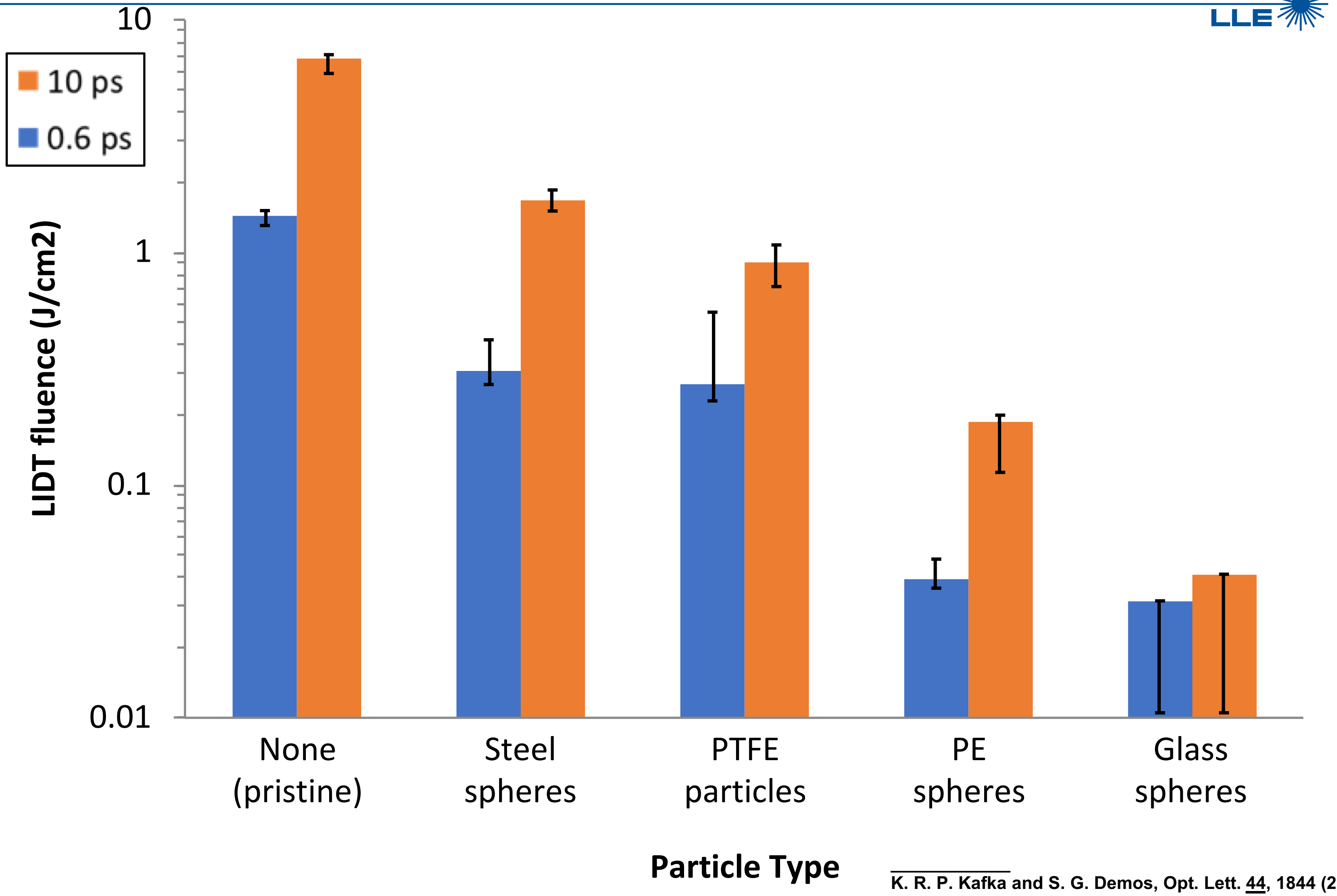
C. W. Carr, *et al.*, "Damage sources for the NIF Grating Debris Shield (GDS) and methods for their mitigation" SPIE Proc. 10447, 1044702 (2017).

Damage testing under short-pulse exposure of model contamination particles on a MLD mirror

- **Model contaminant:**
  - **Stainless steel**
  - **Borosilicate glass**
  - **Polyethylene (PE)**
  - **PTFE (Teflon)**
- **Substrate:**
  - **MLD HR mirror**
- **Test protocol:**
  - **1053-nm pulses**
  - **0.6 ps and 10 ps**
  - **45°, *s* polarization**
  - **Air environment**

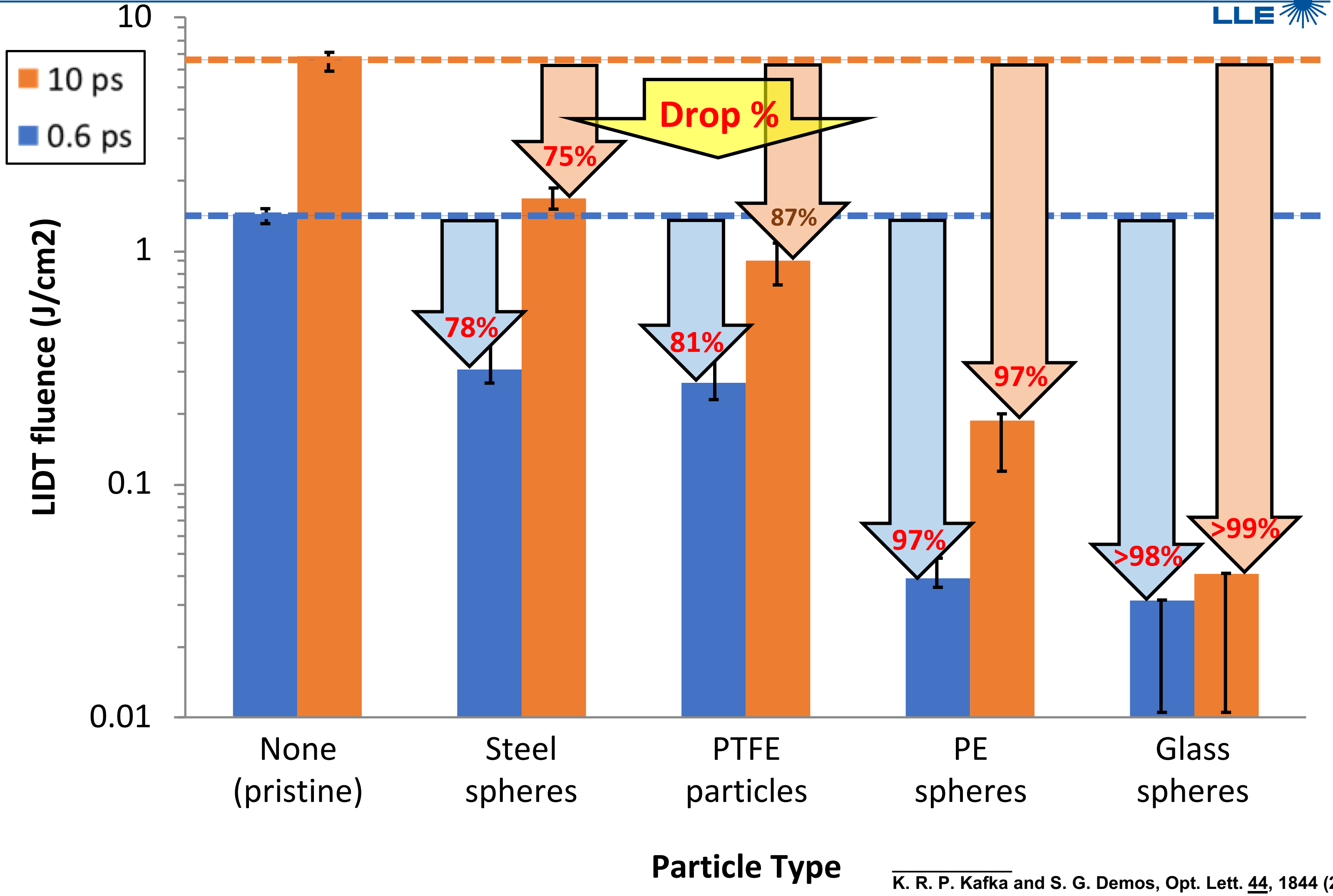


K. R. P. Kafka and S. G. Demos, Opt. Lett. 44, 1844 (2019).

Damage testing under short-pulse exposure of model contamination particles on a MLD mirror

Thresholds of ejection and damage initiation are reduced from the pristine 1-on-1 LIDT:

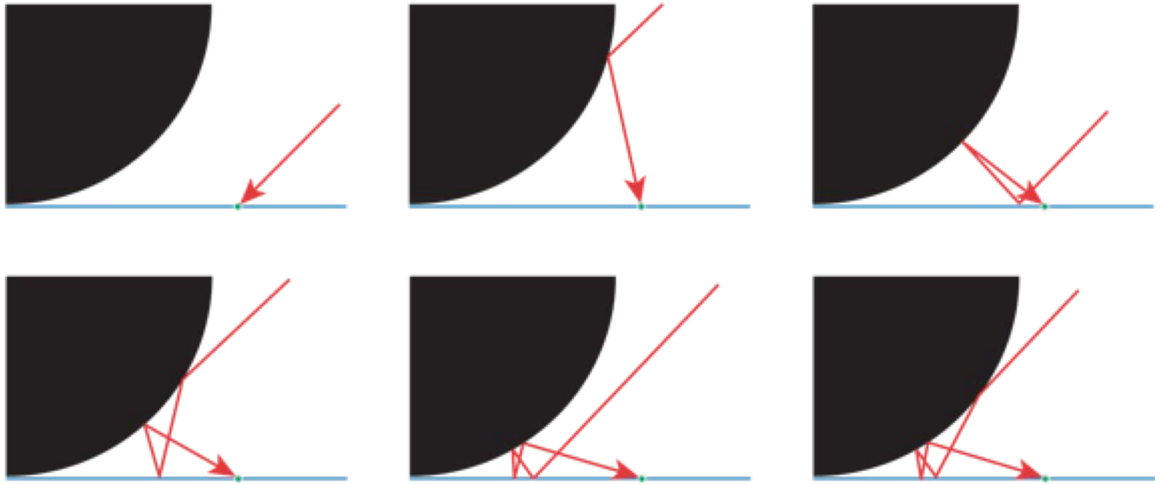
- **>95% for dielectric quasispheroidal particles**
- **>20% for metallic and irregularly shaped dielectric particles**



"Error" bars indicate the 0% to 100% damage probability range

K. R. P. Kafka and S. G. Demos, Opt. Lett. 44, 1844 (2019).

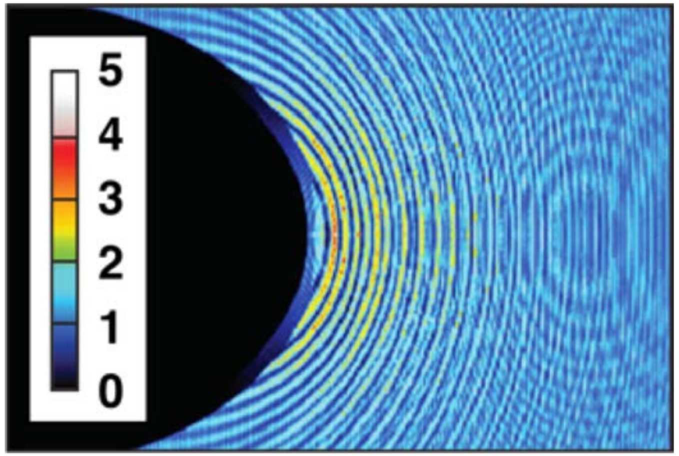
Case example: Metal sphere on a reflective surface, experimental and modeling study



G13071

- **The interference of multiple orders of waves on the surface creates an intensity pattern that matches the experiment***
  - **experimental damage threshold reduction factor 4.3±0.3 (45° incidence, *s* polarization, 0.6-ps duration)**

Maximum intensity factor: 4.3



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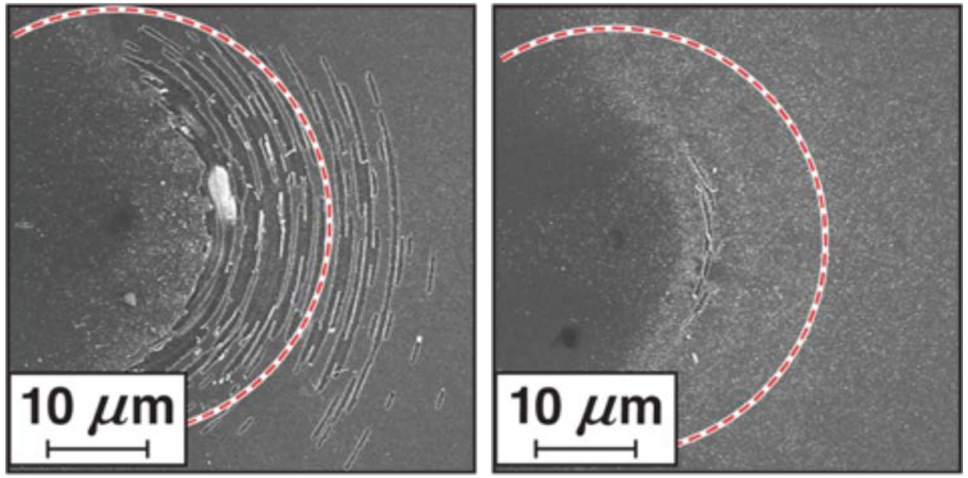
Model

Experiment



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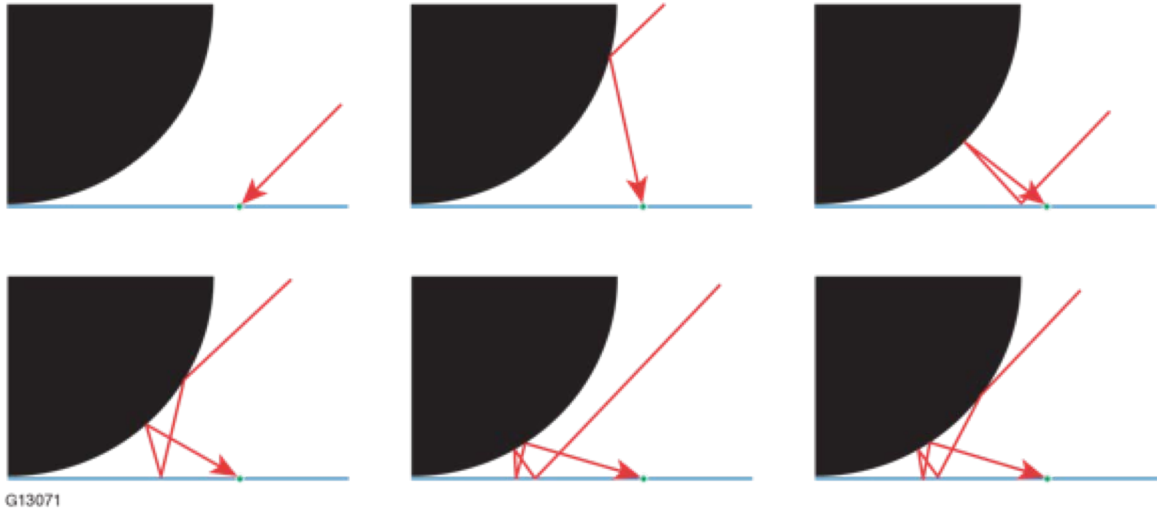
* K. R. P. Kafka et al., “Mechanisms of Picosecond Laser-Induced Damage from Interaction with Model Contamination Particles on a High Reflector,” submitted to Optical Engineering.

Case example: Metal sphere on a reflective surface, experimental and modeling study



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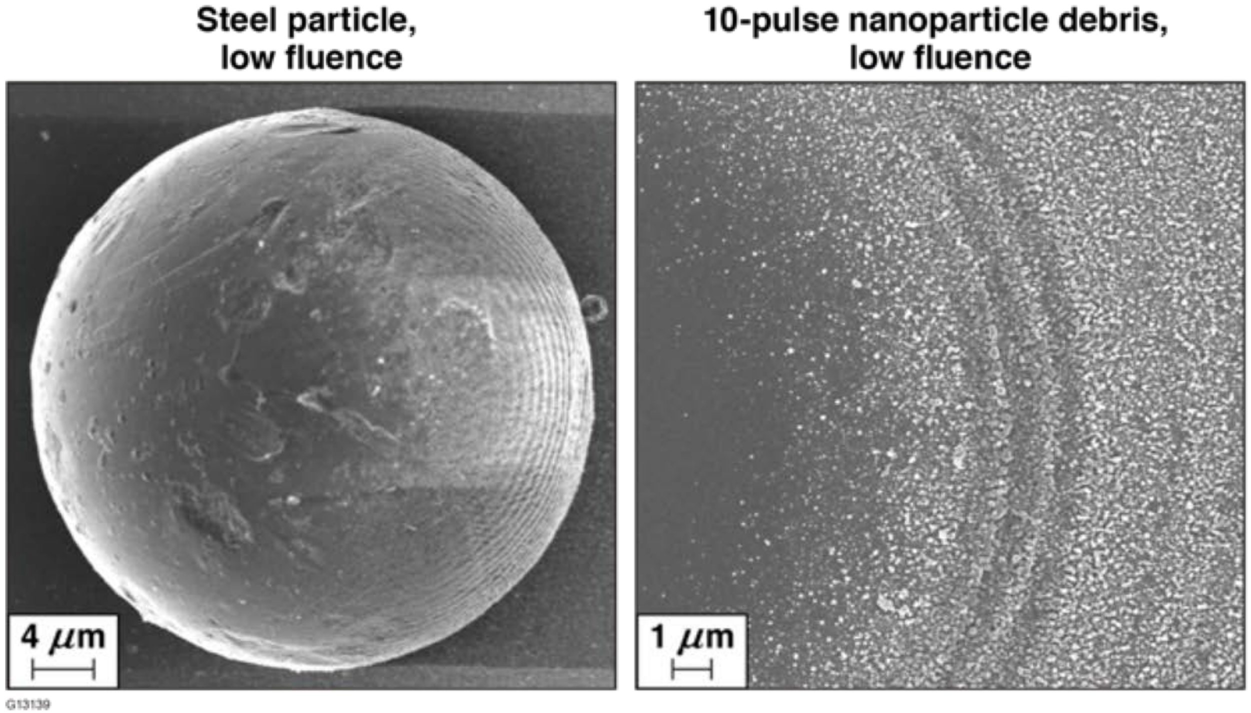
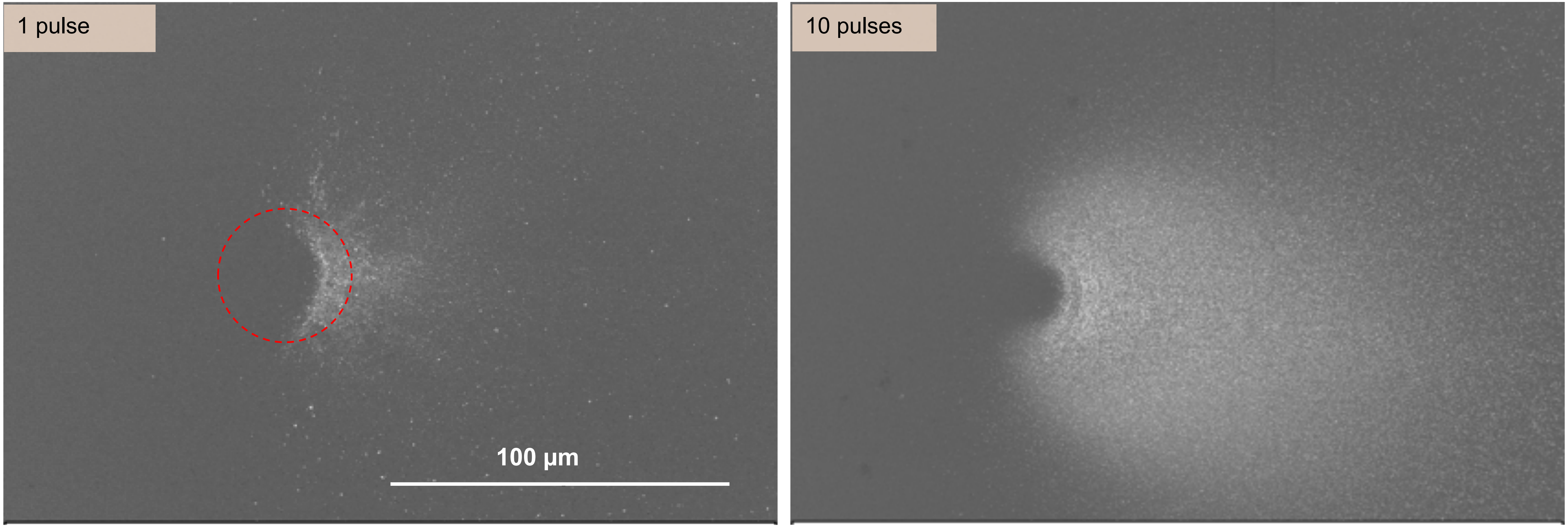


K. R. P. Kafka and S. G. Demos, Opt. Lett. 44, 1844 (2019); K. R. P. Kafka *et al.*, "Mechanisms of Picosecond Laser-Induced Damage from Interaction with Model Contamination Particles on a High Reflector," submitted to Optical Engineering.

Metal particles generate secondary nanoparticle contamination that can extend hundreds of μm from the original site

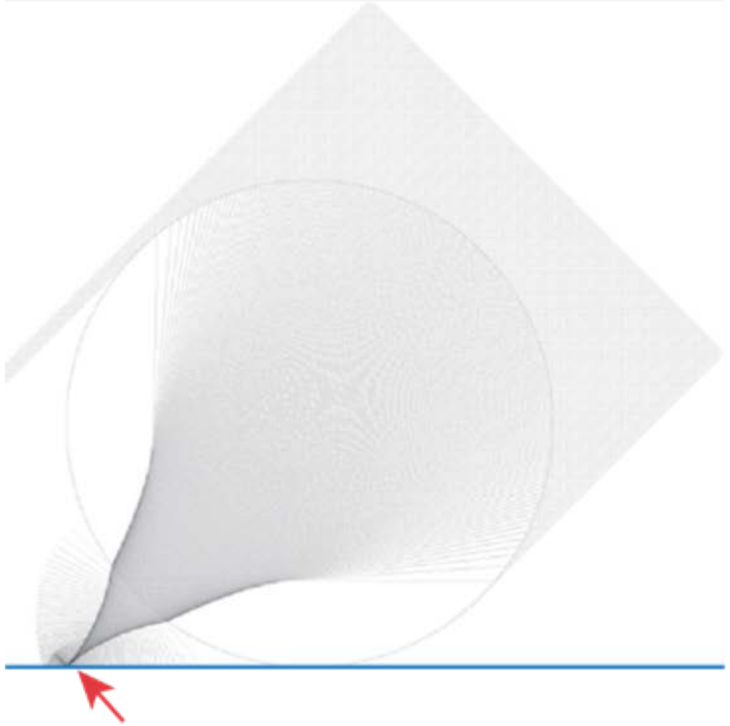
- **Particle exposed to 0.2 J/cm^2 (14% LIDT), 0.6 ps pulses. PARTICLE NOT EJECTED by the laser**



- **Increased fluence → wider contaminated area**

Case example: Transparent dielectric sphere on reflective surface, size larger than the wavelength

Model



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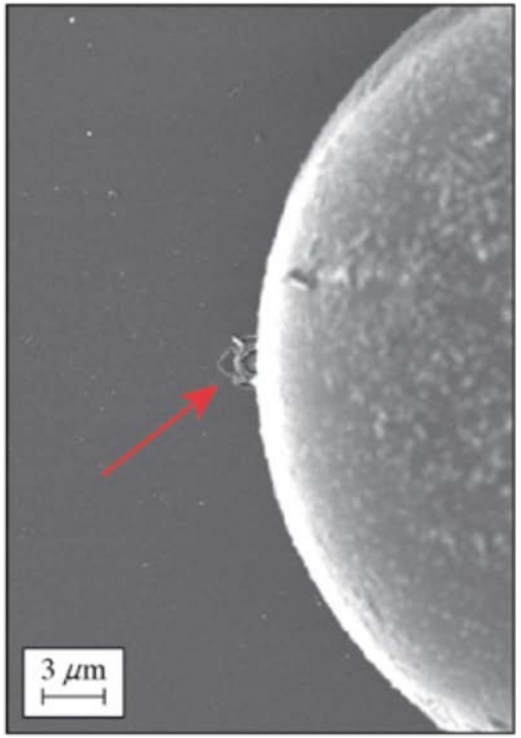
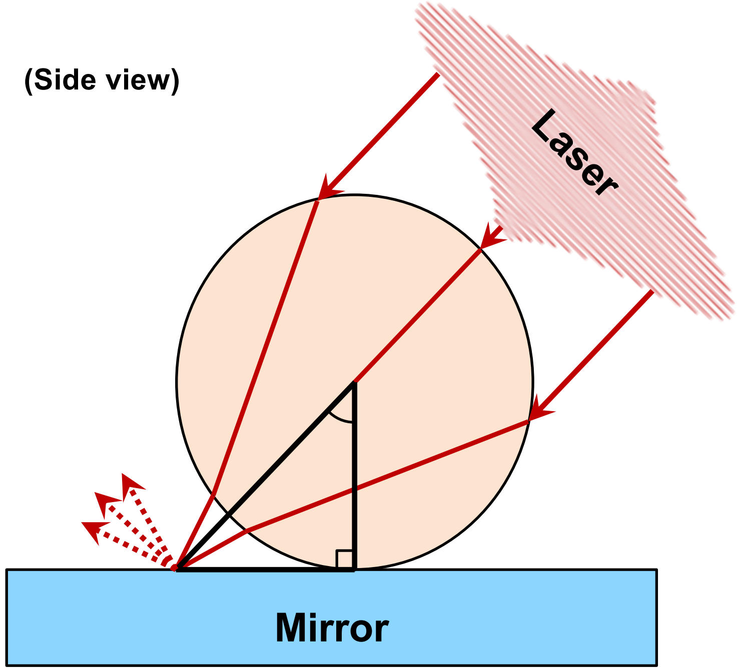
Experiment

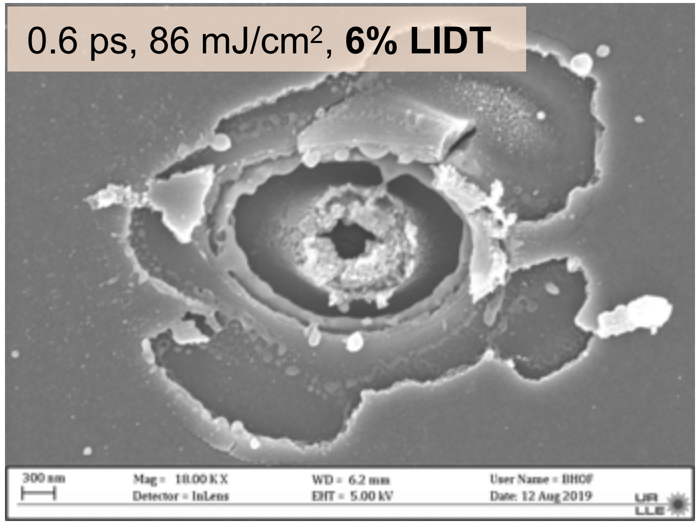


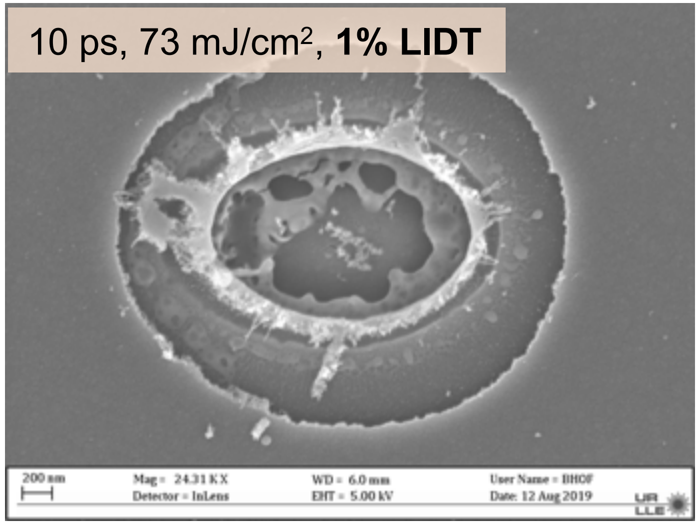
- The ray-tracing model is constructed to calculate the field distribution inside and outside the sphere
- There is a focal spot near the exiting surface;
  in paraxial approximation this is infinitely small but there are significant aberrations
- The hot-spot intensity scales with (R/λ)^2
  – the experimental damage threshold reduction factor is >160

Maximum intensity factor: 200 on a flat surface, 8 to 13 on exit spherical surface of particle.

Quasispheroidal transparent particles act as micro lenses, focusing the laser near the surface of the optic





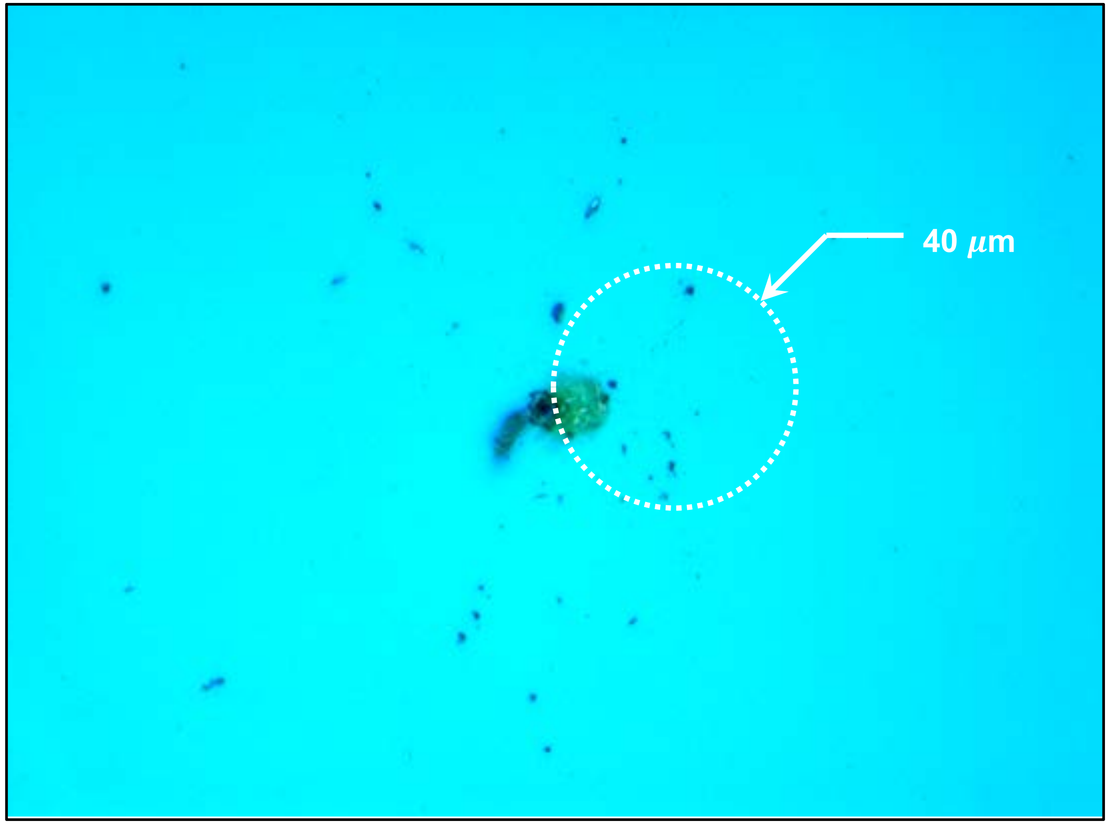


- **Intensity is also enhanced at the exit surface of the particle due to the converging beam**
- **An ablation crater on the mirror is generated at very low laser fluences**

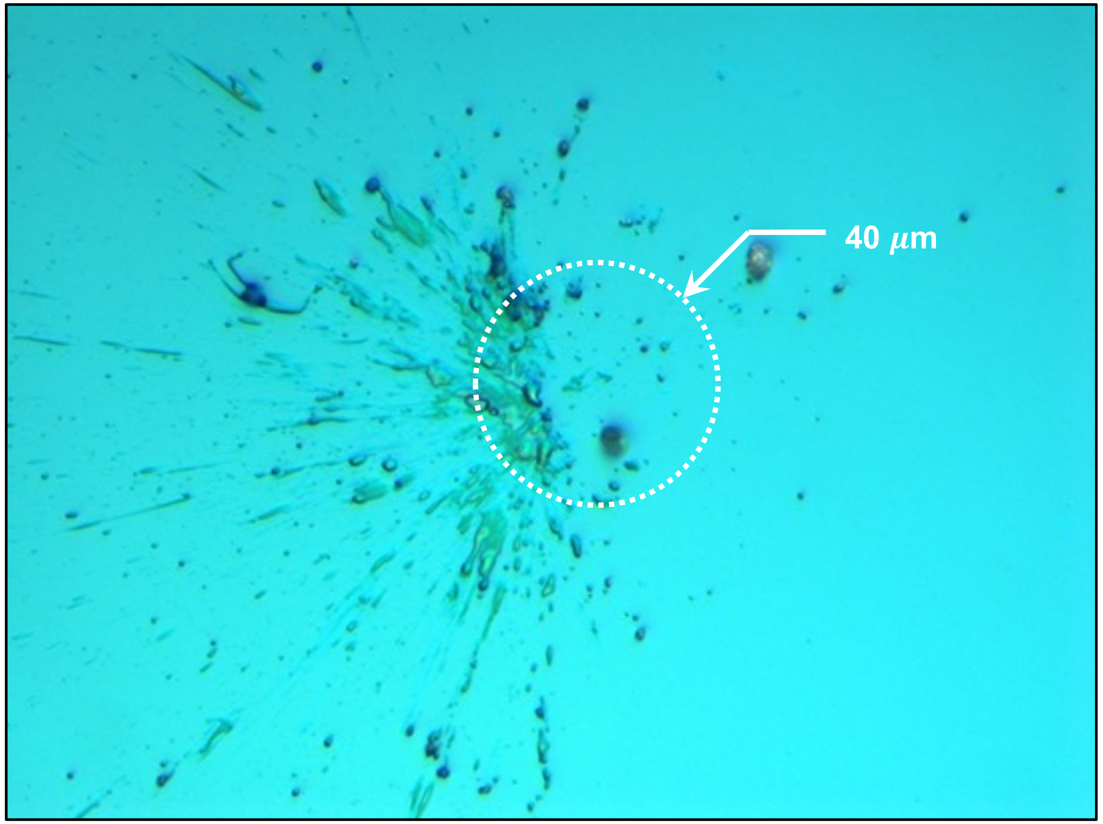
The ablation crater extends multiple layers within the MLD

As fluence increases, explosive fragmentation of the particle becomes a source for extensive secondary contamination

Glass particle, 0.6 ps, ≈ 30% LIDT



Polyethylene particle, 0.6 ps, ≈20% LIDT

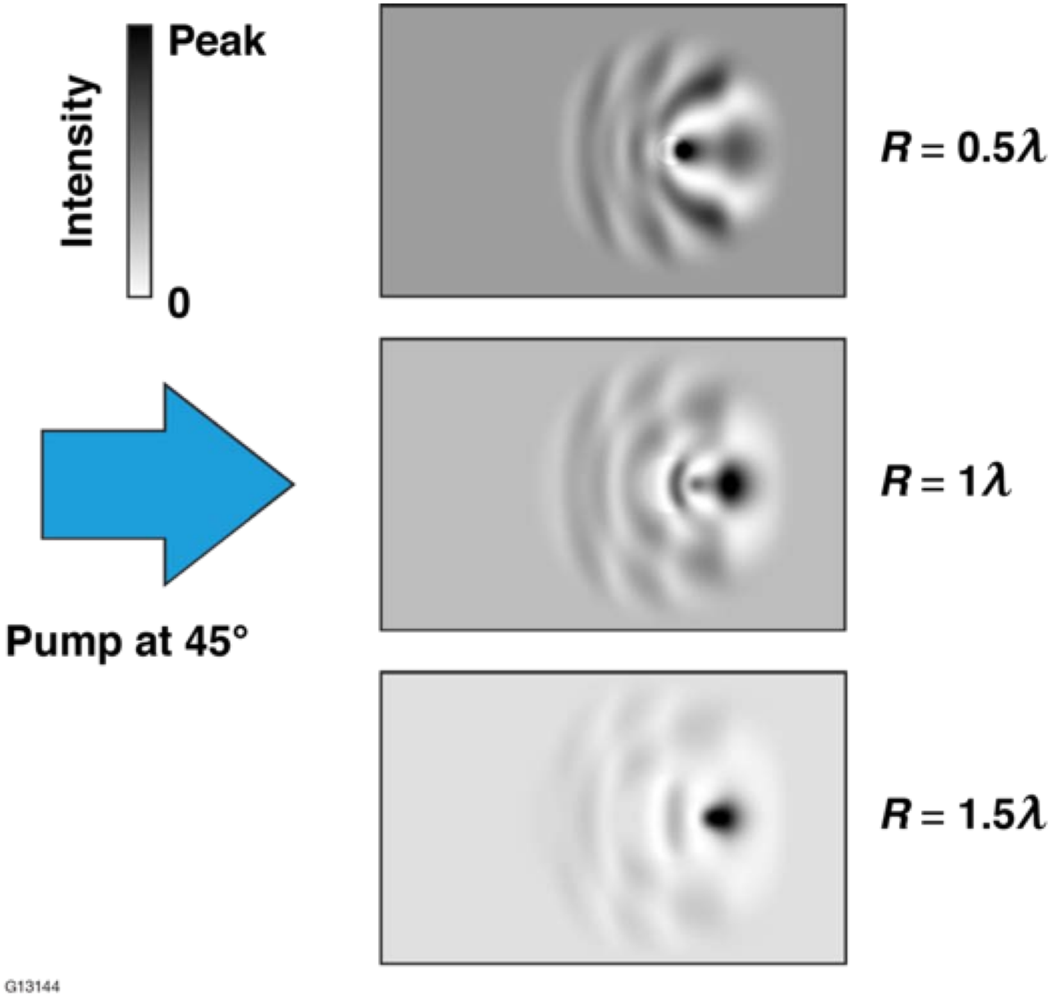


Secondary contamination causes additional damage and damage growth in subsequent exposure.

Contamination particles that are smaller than the laser wavelength also pose significant risk

- For particles smaller than the wavelength, the shape does not play a significant role in the field enhancement
- The density of debris can become an important factor arising from coherent interference between the scattered fields of adjacent particles
- The scaling law EFI $\propto (R/\lambda)^2$ does not apply to particle sizes $< \lambda$
- Case example: dielectric sphere
- There is a hot spot behind the particle

Maximum intensity factor
- 1.42 for $R = 0.5\lambda$
- 2.84 for $R = 1\lambda$,
- 6.26 for $R = 1.5\lambda$



Implementation of contamination control protocols is critical in high-intensity, short-pulse laser applications

- Contamination particles of size down to 1/4 wavelength can significantly decrease the effective LIDT via different mechanisms:
  - Produce a scattered field, which either by itself or combined with the incident laser field can give rise to regions having electric-field enhancement
  - Support field enhancement on the particle, leading to its disintegration or ablation that generates secondary contamination with smaller particles
  - Generate ablation plasma that can modify the adjacent area of the substrate
- Secondary contamination is a risk factor for the longevity and damage performance of optical components exposed to peak intensities
- Development of an effective way of detecting potentially dangerous contamination by particles may be of paramount importance in certain applications

Summary

Attaining high laser-damage performance requires optimization of materials, designs, and operational parameters

- There are a number of mechanisms that can facilitate damage initiation. Arguably, the primary mechanisms involve two main classes:
  - Defects, in the form of clusters (typically of the order of 50 nm) and/or atomic defects incorporated in the material during the manufacturing/deposition process
  - Contamination by micro- or nanoscale particles or organic species from handling, the operational environment, or the manufacturing process
- Achieving and maintaining high damage performance requires:
  - Optimization of the optical designs with selection of materials and manufacturing process for the intended operational parameters (wavelength, pulse durations, etc.)
  - Control of contamination issues (during manufacturing and operation)
  - Management of damage growth for large-aperture systems