Laser damage resistance of optical coatings in the sub-ps regime: limitations and improvement of damage threshold

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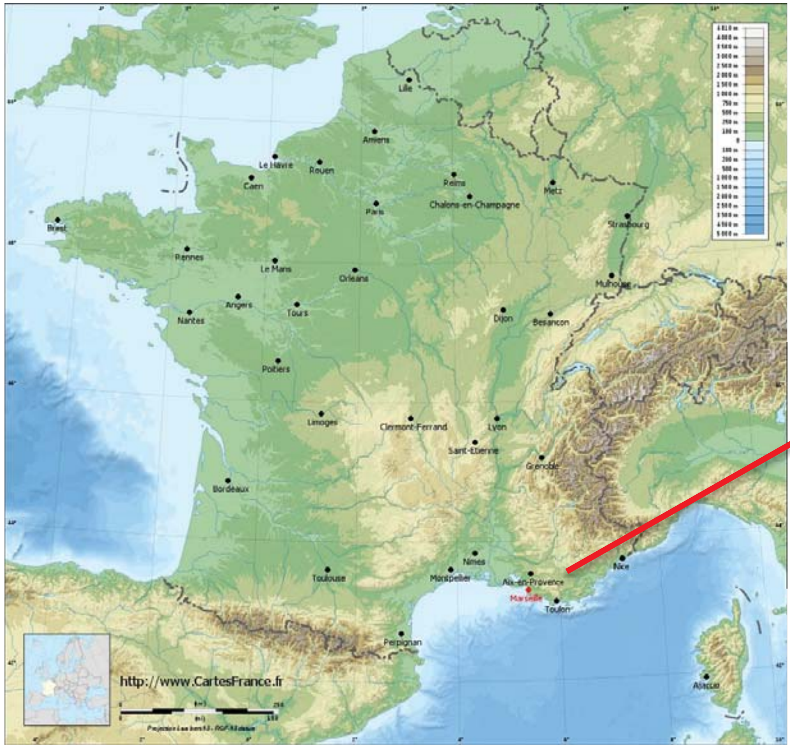

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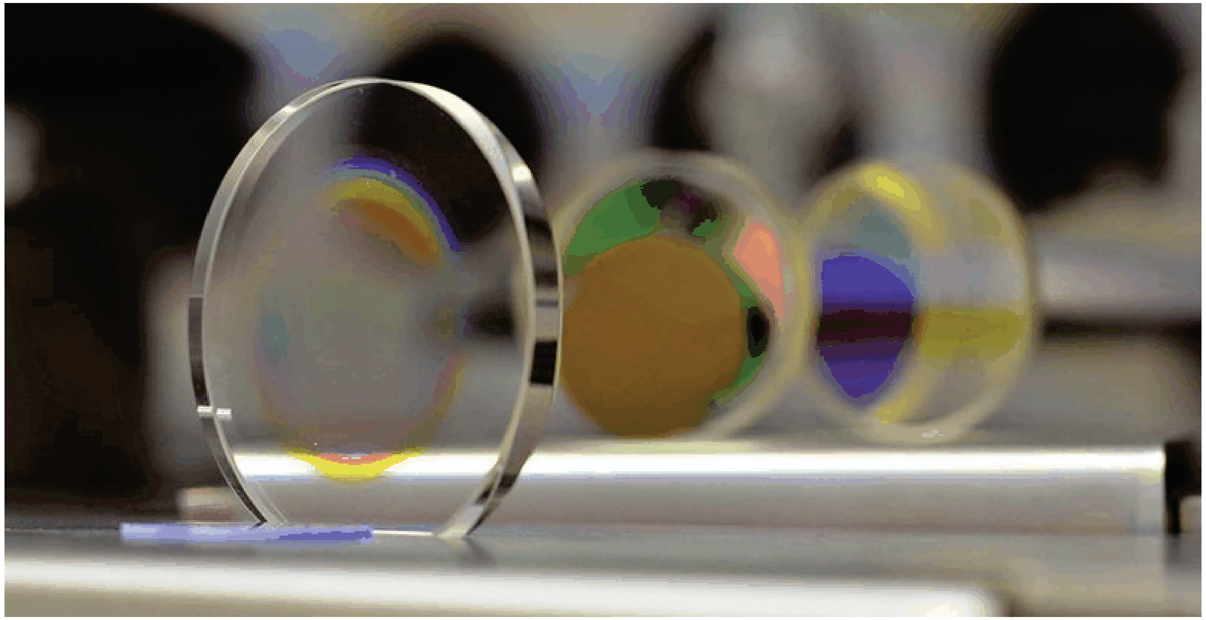

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Plasmonics
Optical components
Optical thin films
Laser damage and processing

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Optical Coating group

- Topics:
  - High performances optical interference filters
  - Innovative concepts and components
- Staff:
  - 7 permanent, 2 PhD
- Equipement:
  - 250m² clean rooms
  - 5 different machines with in situ optical monitoring: EBD, IAD, PIAD, DIBS, PARMS
  - Commercial and custom characterization systems

Laser Material Interaction group

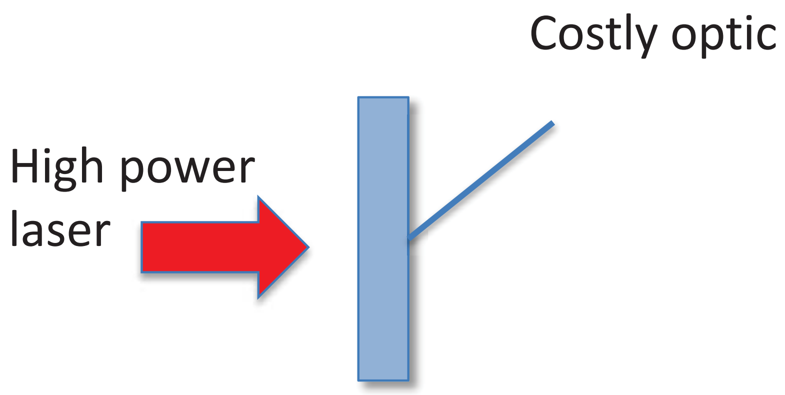
- Topics:
  - Physics of laser material interactions (fs to CW)
  - Laser damage of optical components for high power applications
  - Laser processing
- Staff:
  - 6 permanent, 3 post-doc, 7 PhD students
- Equipment:
  - fs & ns LIDT measurements
  - CW laser processing
  - Commercial and custom characterization systems

Introduction

Laser damage

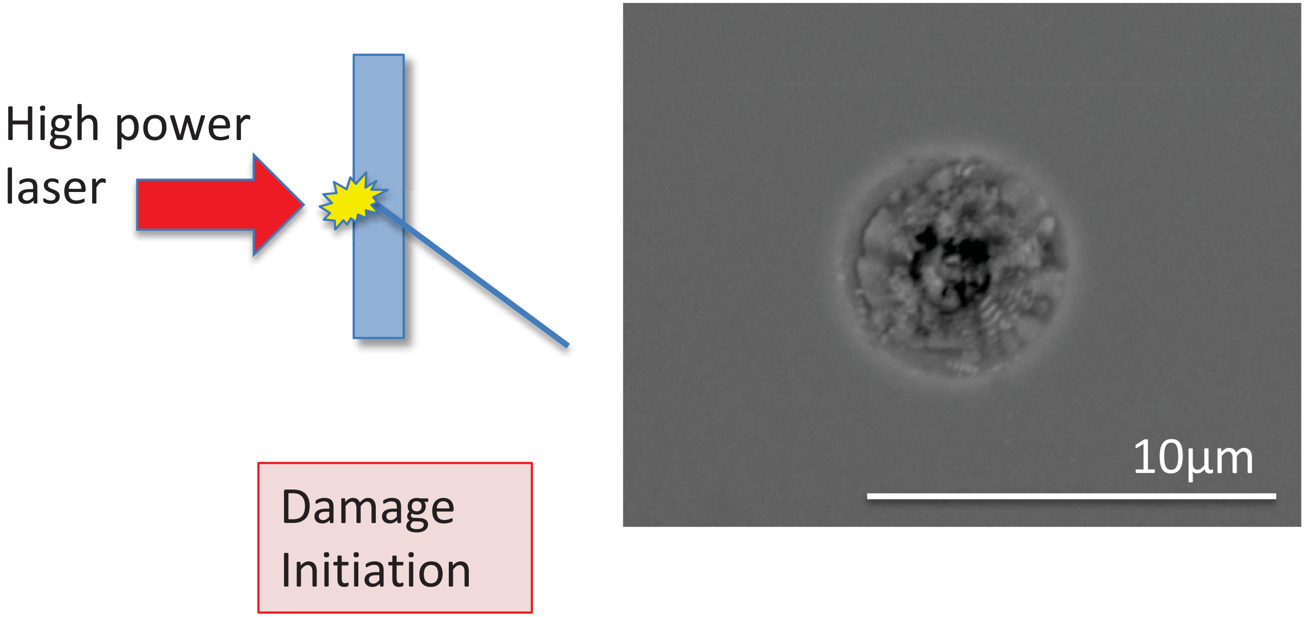
Introduction

Laser damage



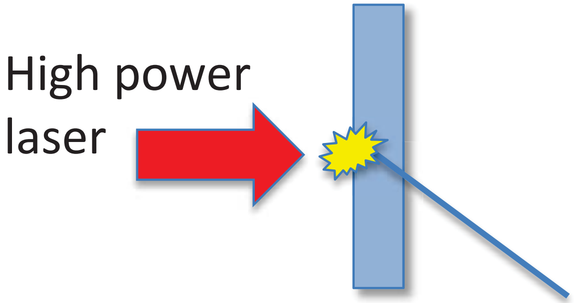
Introduction

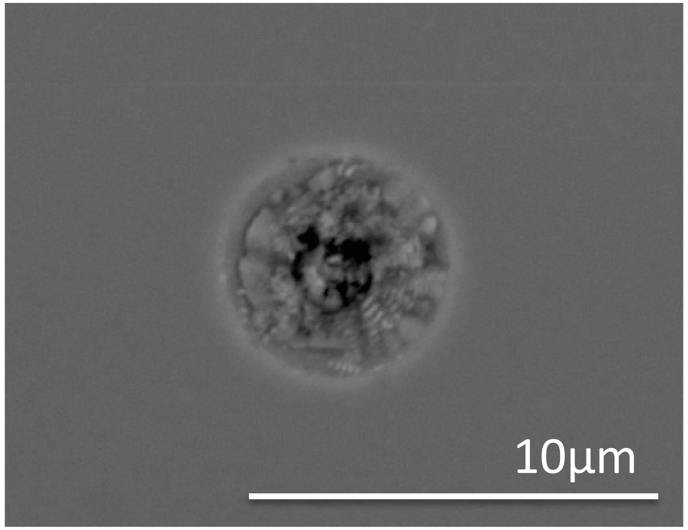
Laser damage



Introduction

Laser damage



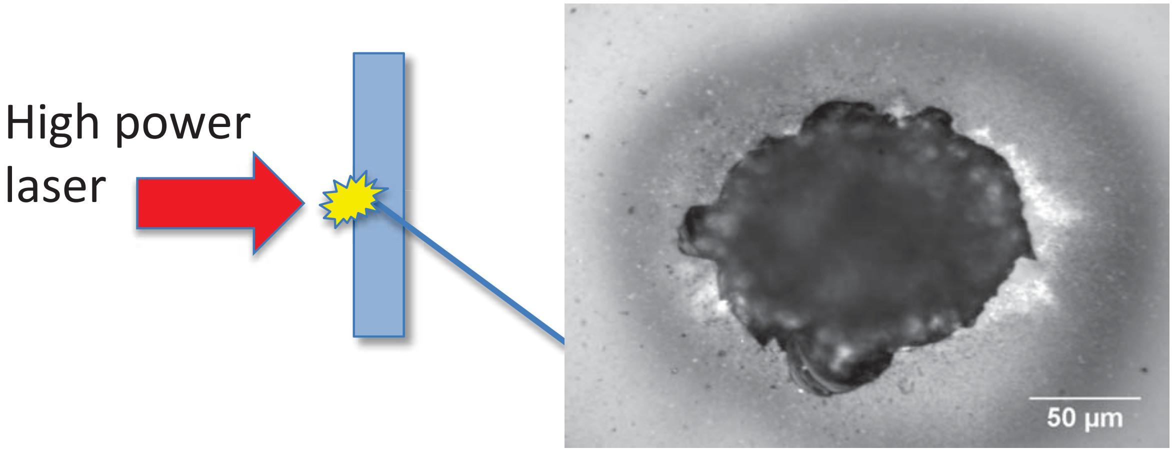


Damage Initiation

→ Local reduction of damage resistance

Introduction

Laser damage

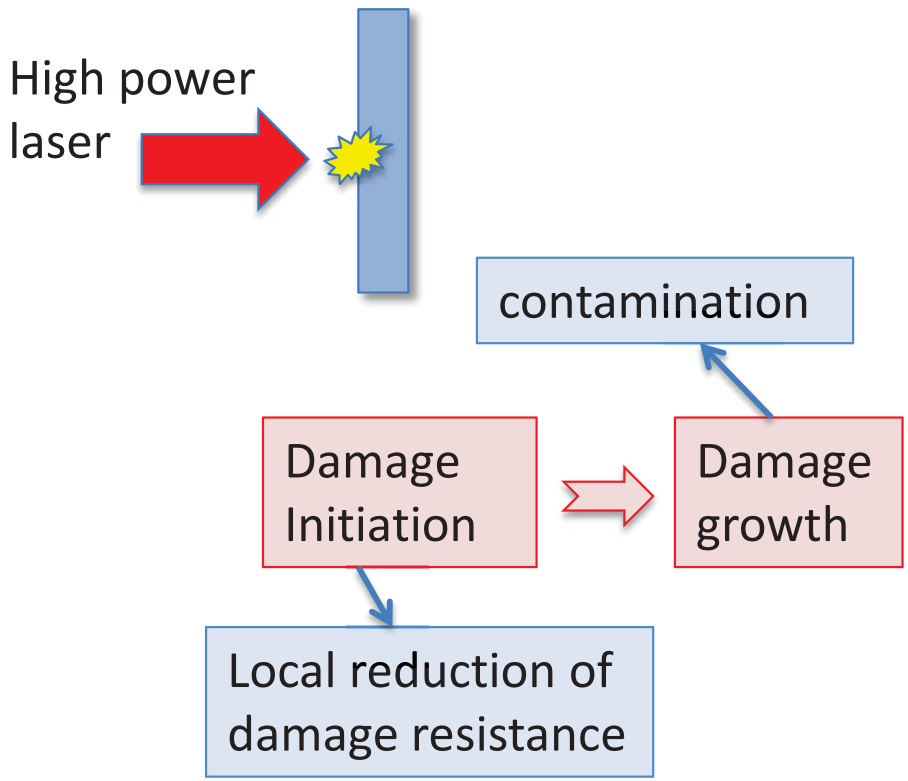


Damage Initiation → Damage growth

Local reduction of damage resistance

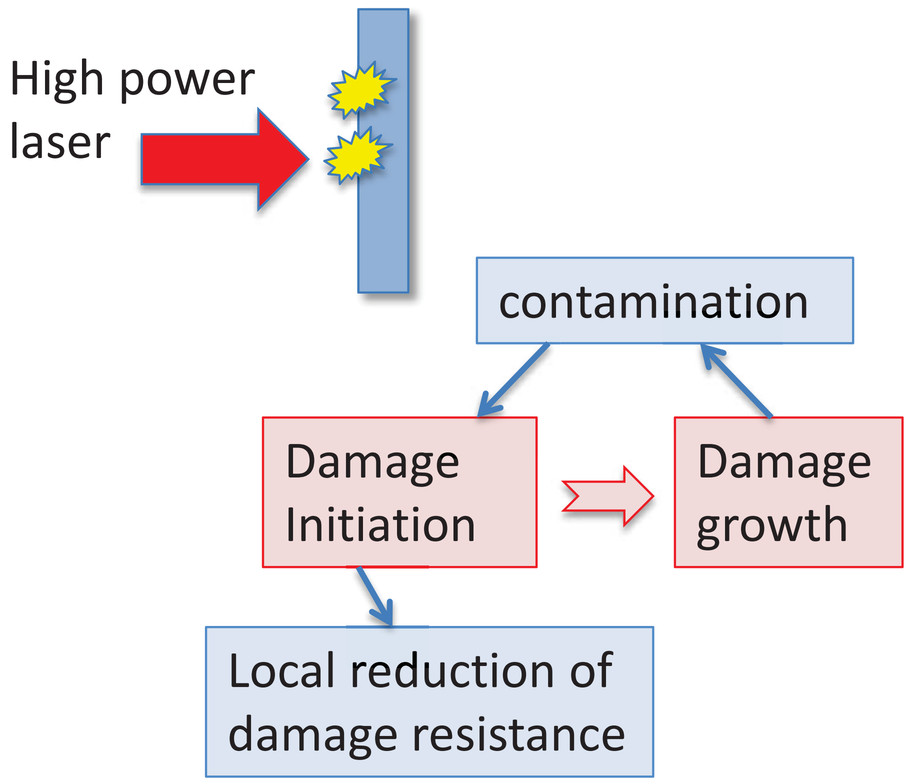
Introduction

Laser damage



Introduction

Laser damage



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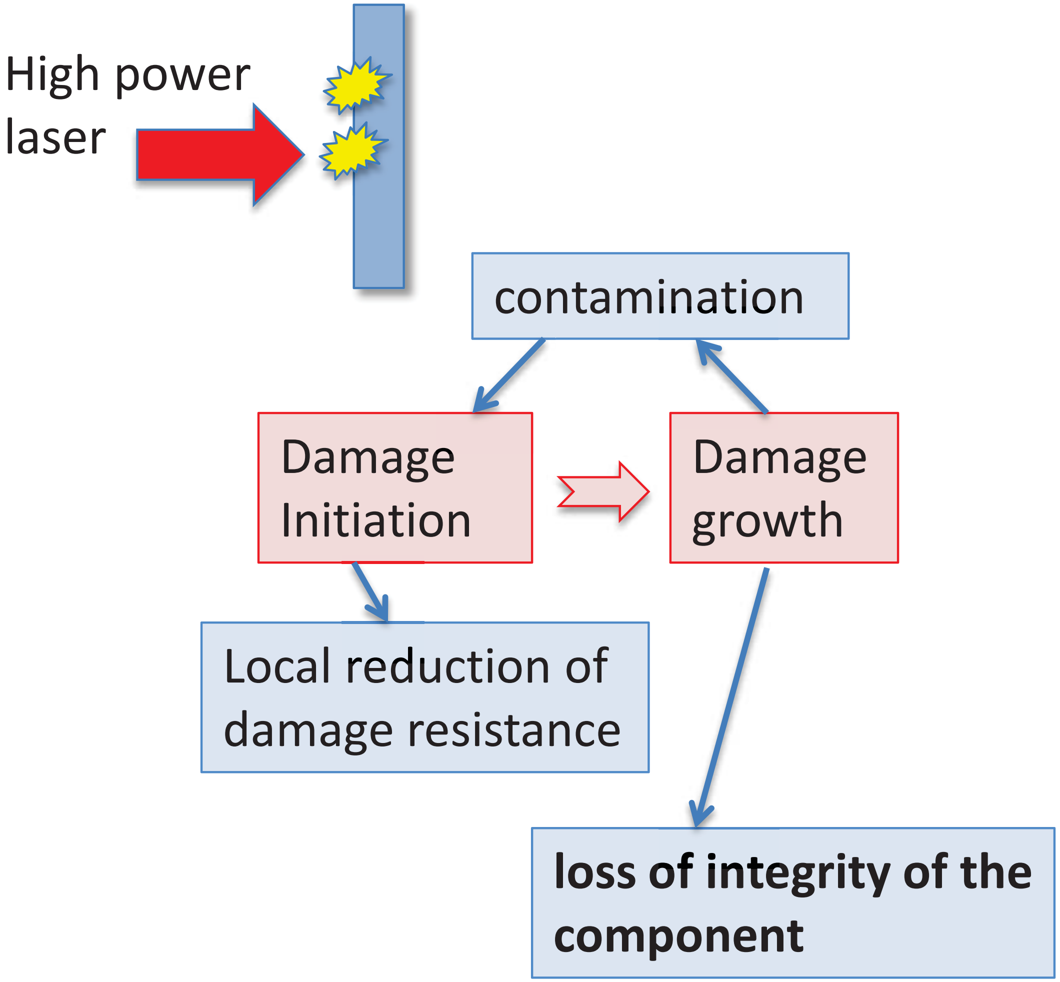
Laser damage



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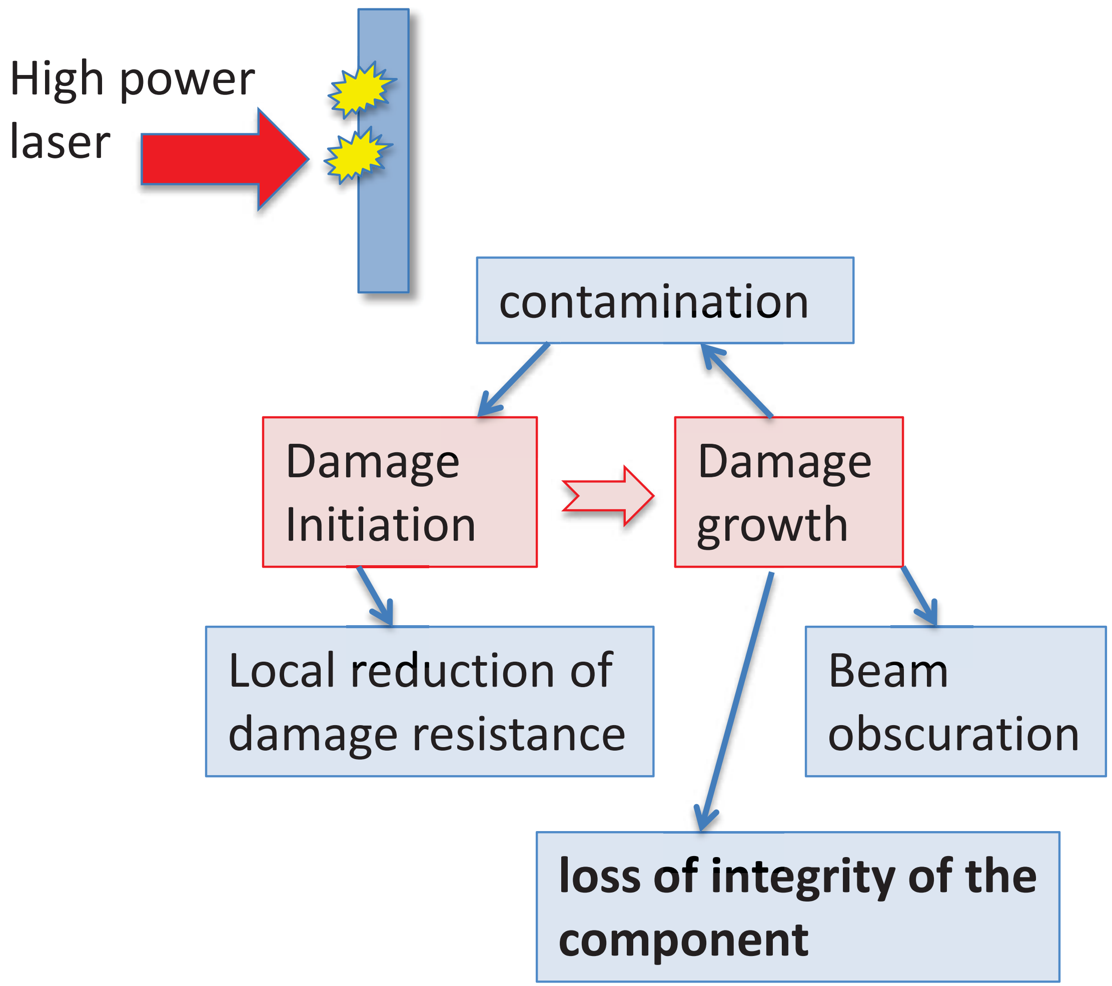

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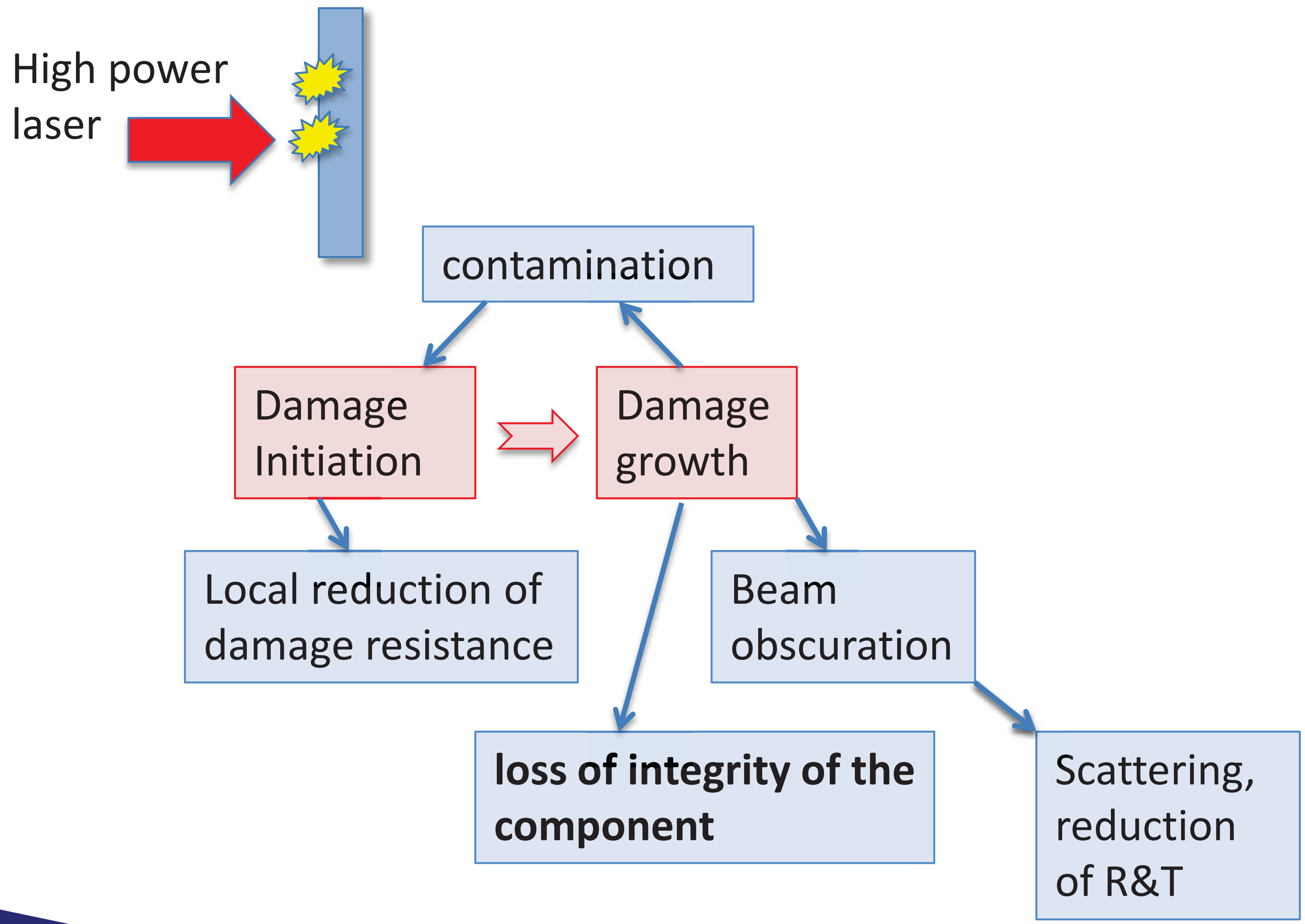

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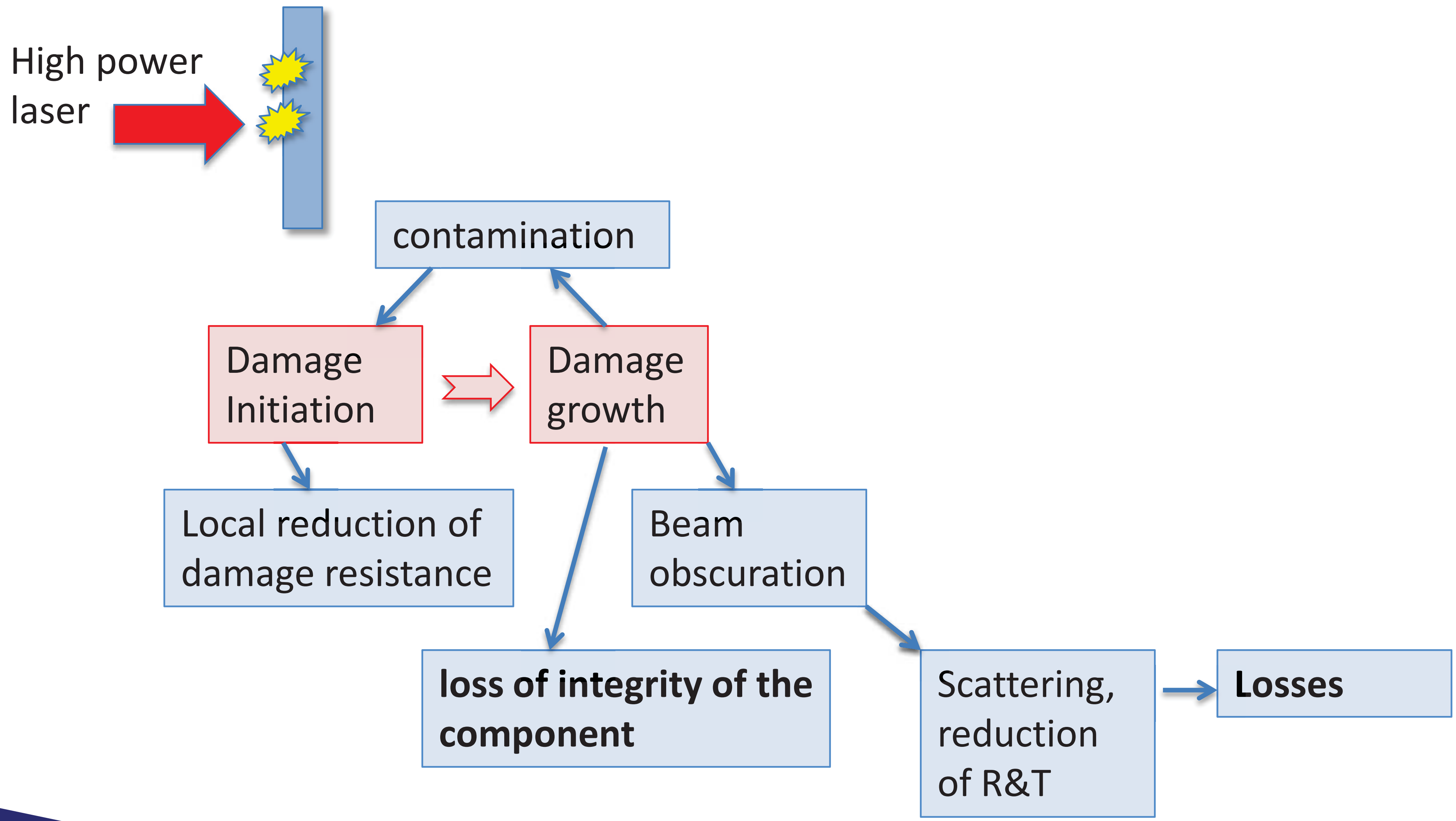

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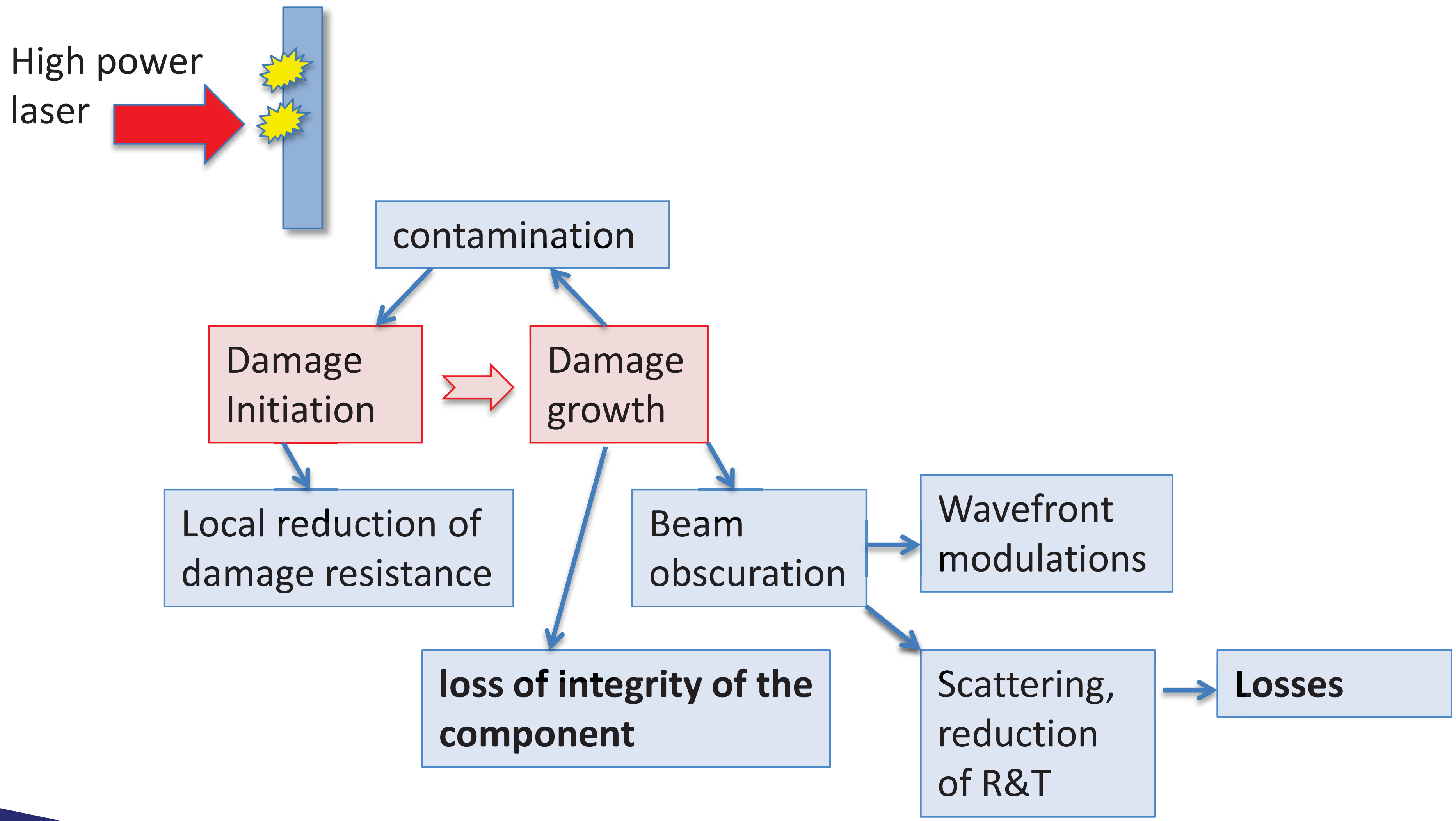

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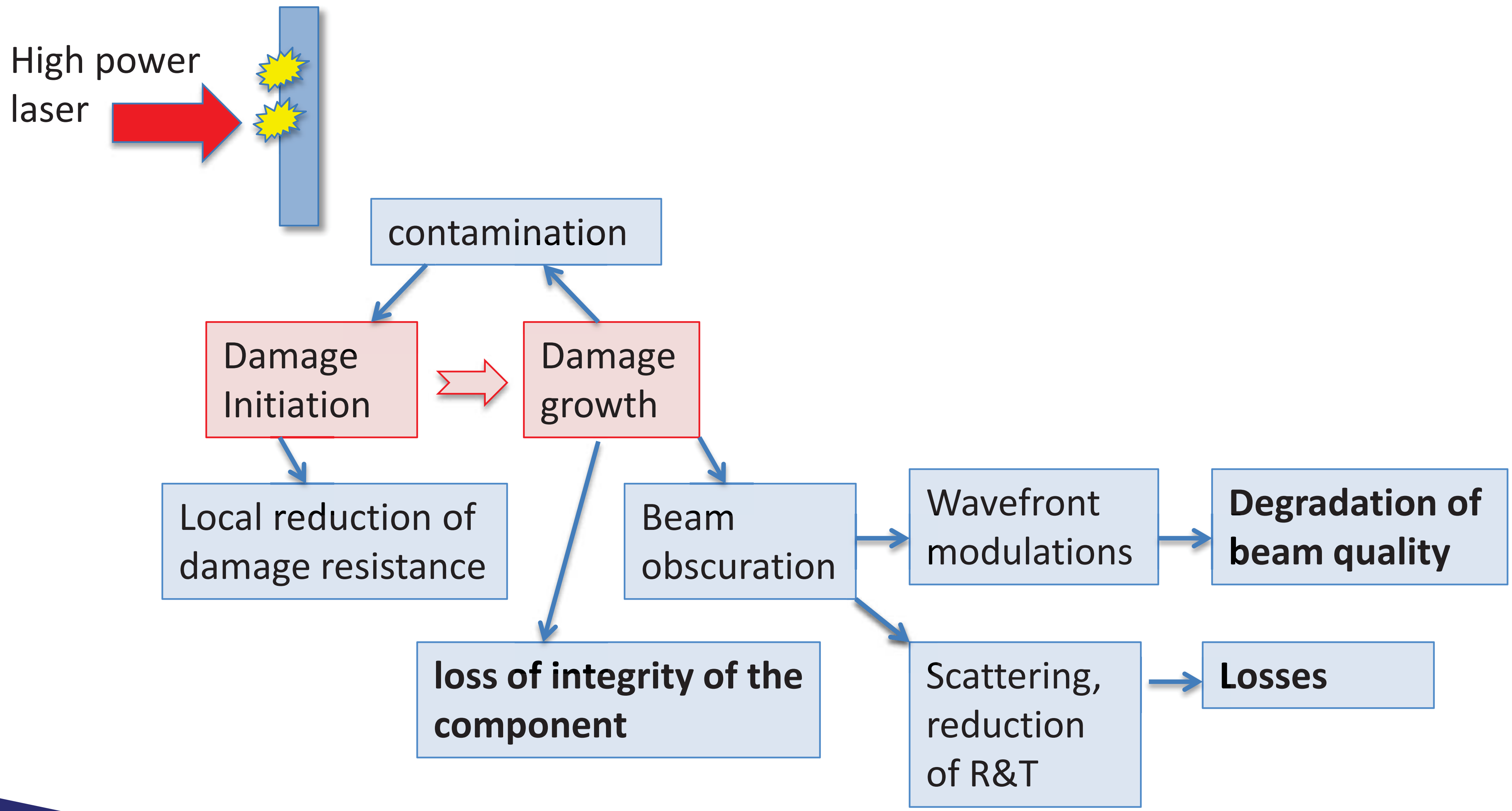
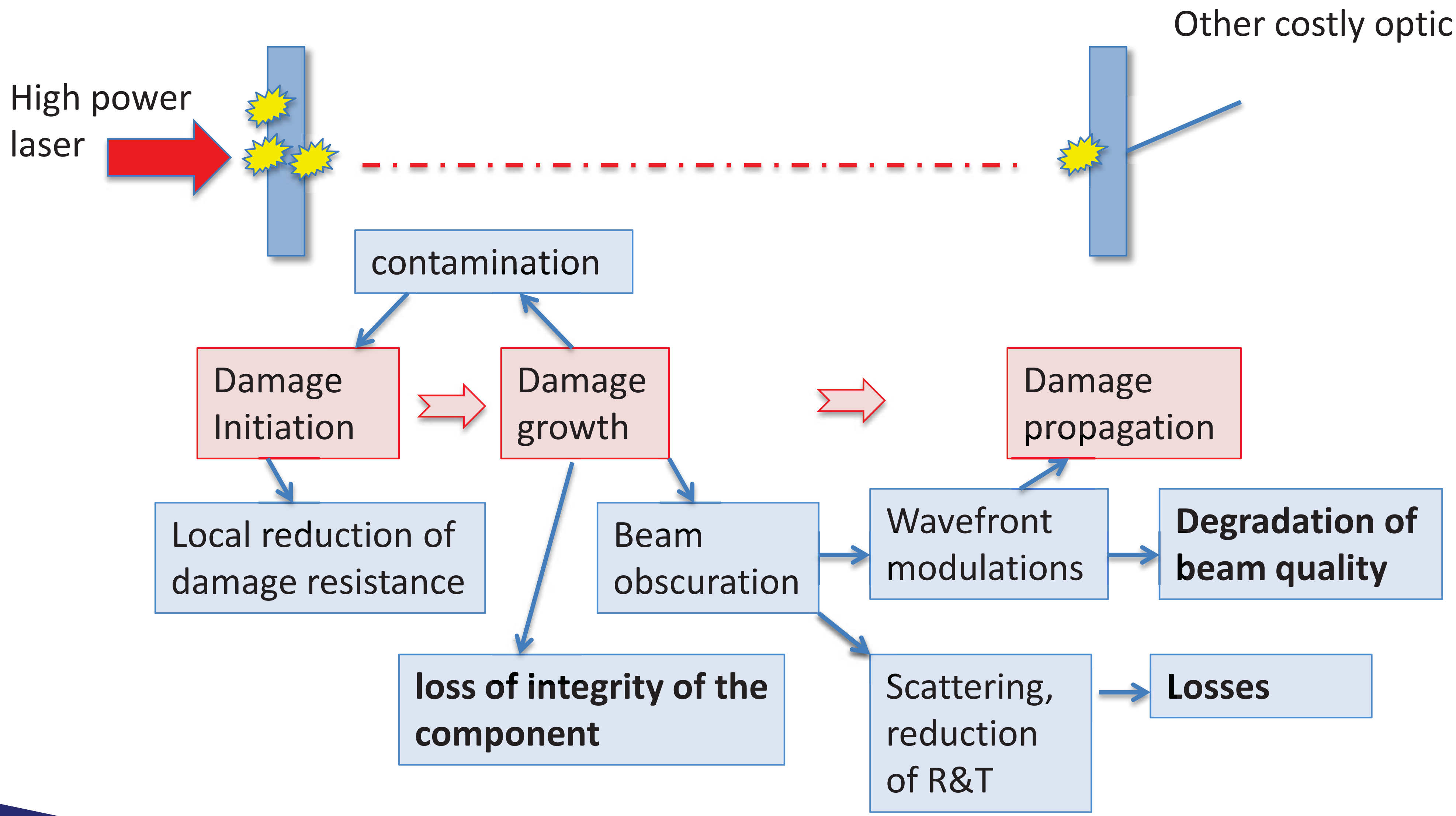
Laser damage



Introduction

Laser damage



Outline

Basics of short pulse laser damage process

Damage resistance of optical materials

Defect-induced laser damage & damage growth

Improvement of laser damage resistance

Outline

Basics of short pulse laser damage process

Damage resistance of optical materials

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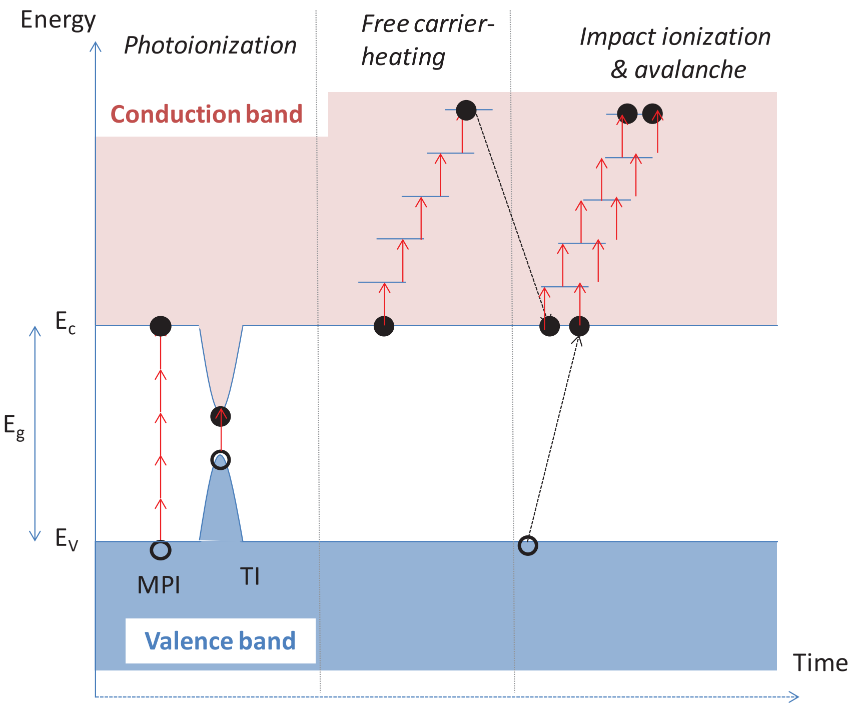
Improvement of laser damage resistance

Basics of short pulse laser damage process

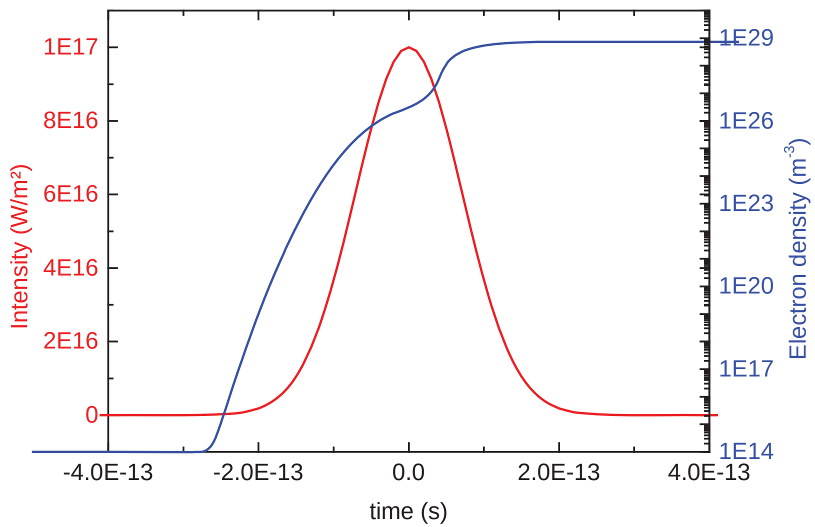
Non-linear ionization

Ionization processes under high intensity illumination



Schematic representaion of Multi-Photon Ionization, Tunnel Ionization, Impact Ionization and Electronic Avalanche

« free » electron generation evolution during the pulse

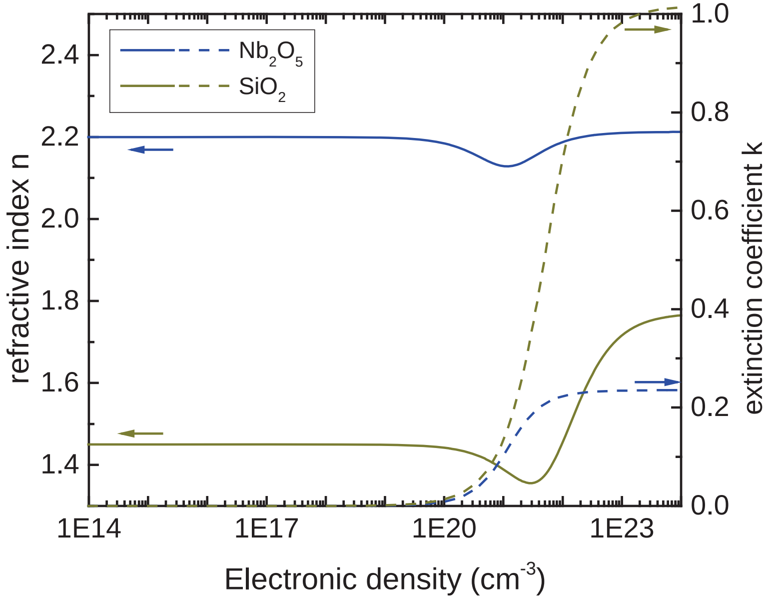


Case of HfO_2 film (5.5eV), at 800nm, 100fs, 1J/cm²

Basics of short pulse laser damage process

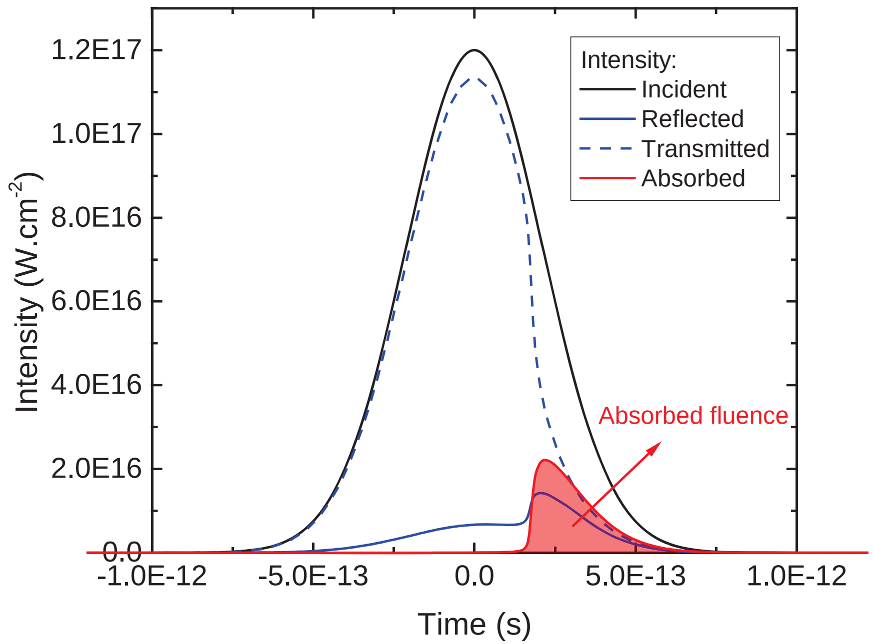
Energy deposition in the material

The material becomes strongly absorbing due to free electron response



*Evolution of the real and imaginary part of the refractive index as a function of free electron density, as described by Drude model**

Significant absorption of the laser intensity occurs due to optical properties evolution



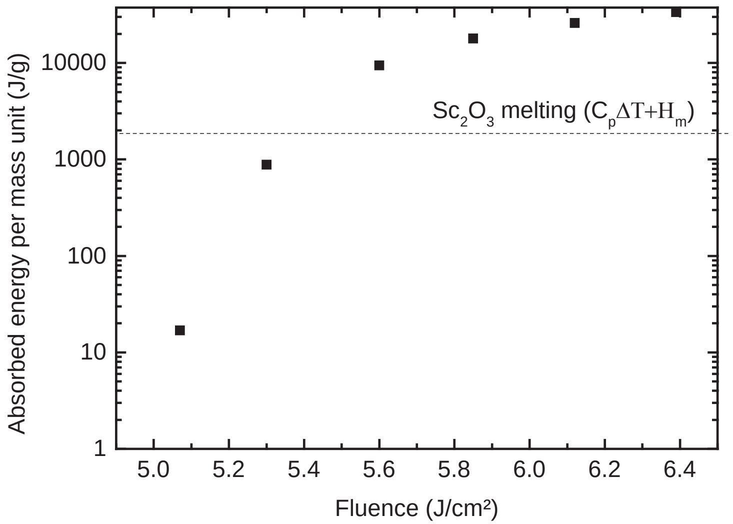
*Intensity as a function of time in the case of a Ta_2O_5 film irradiated with a 500fs, 1030nm pulse.**

*L. Gallais et al., Appl. Phys. Lett. 97, 051112 (2010)

Basics of short pulse laser damage process

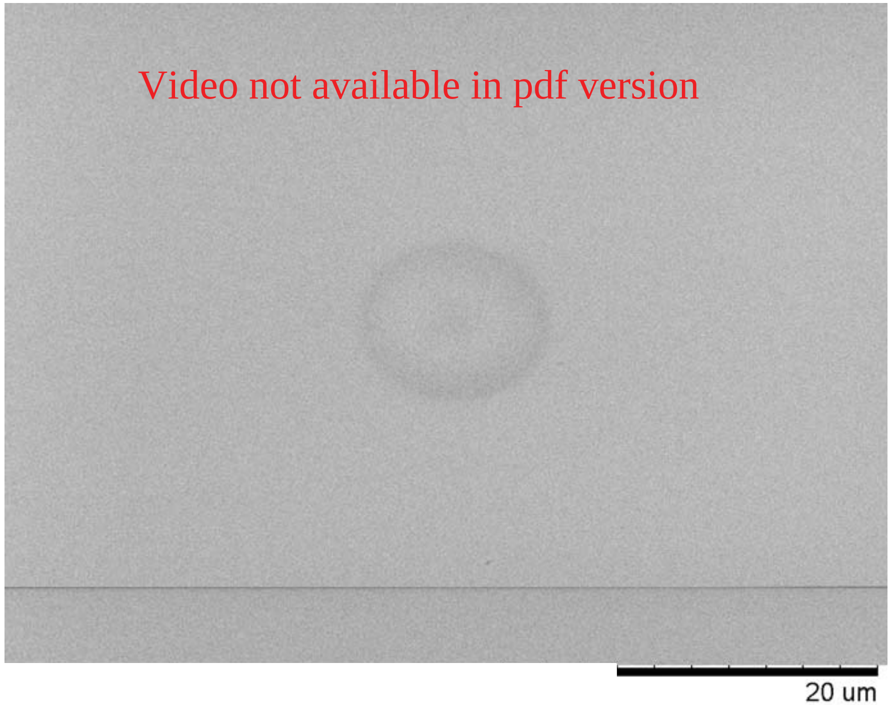
Damage

Damage of the material takes place when the deposited energy is sufficient to cause material modifications



*Calculation of energy per unit of mass deposited in a Sc_2O_3 film with 500fs at 1030nm **

Thermal or mechanical processes lead to material removal



*Hafnia film submitted to different fluences at 500fs/1030nm (each image is a different site)**

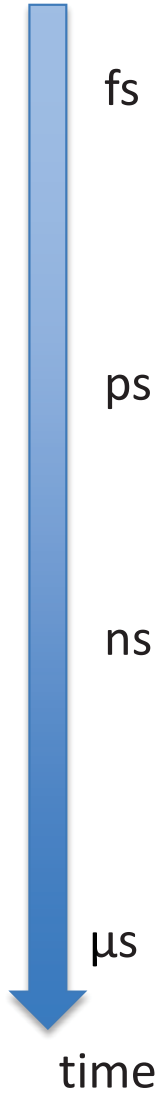
*D.B. Douti et al., Appl. Phys. A., to be published

Basics of short pulse laser damage process

Time scales

Basic processes occur at different timescales:

- Excitation
  - Absorption by free electrons in the material
    - Initial free electrons in metals
    - Free electrons created by non-linear ionisation in dielectrics
- Energy transfer
  - From electrons to lattice
  - Heat diffusion in the material
- Response of the material
  - Phase change
  - Hydrodynamic motion, shock waves
  - Thermo-mechanical stress
- Material removal
  - Thermal or mechanical effects depending on the deposited energy, material properties and irradiation conditions

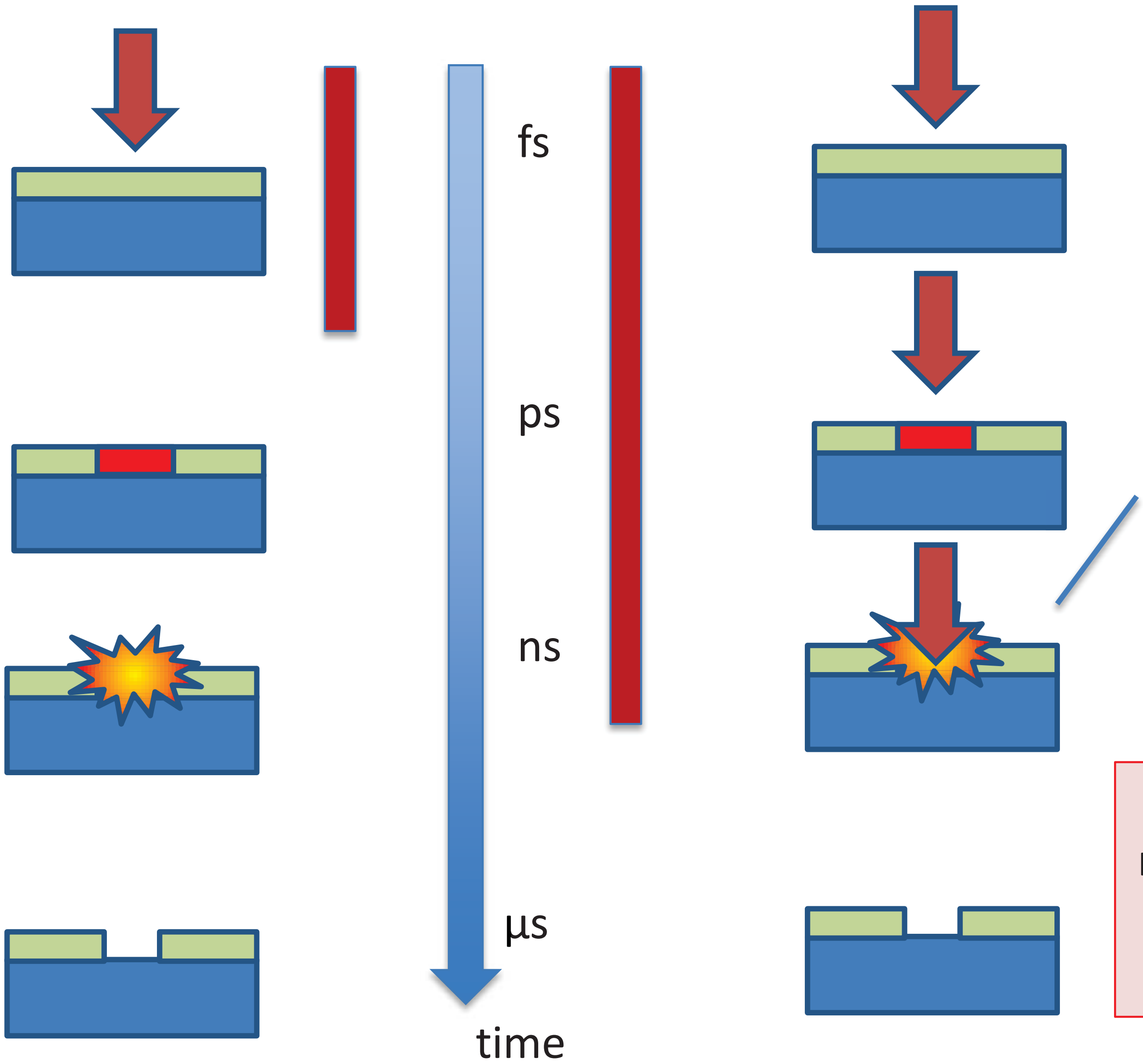


Basics of short pulse laser damage process

Main differences with the ns regime

Energy deposition and damage processes are separated in time

Main property: related to intrinsic properties of the material



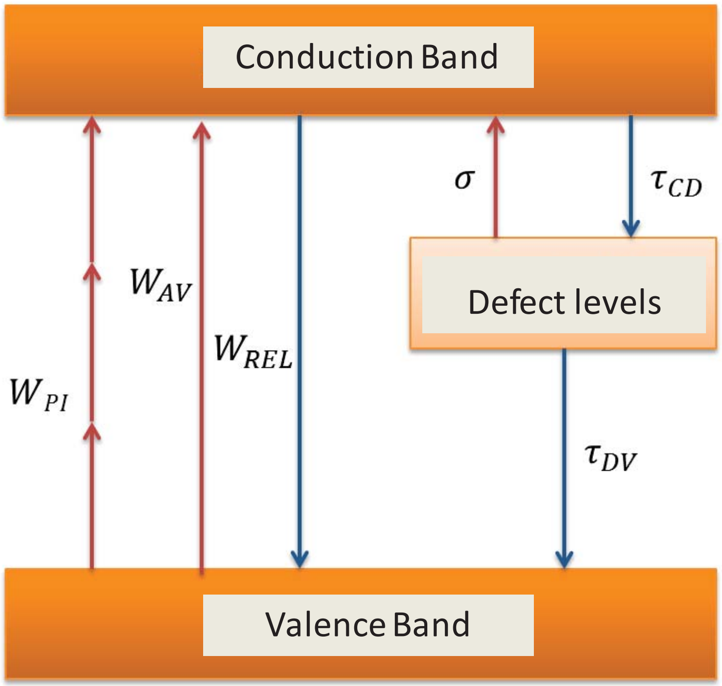
Laser / plasma interaction will drive energy deposition and damage process

Main property: related to defects that can iniate a plasma

Basics of short pulse laser damage process

Material modifications under multiple pulses

Incubation effect related to the accumulation of electronic defects



The different pathways for excitation, relaxation and trapping of electrons, characterized with a rate/lifetime

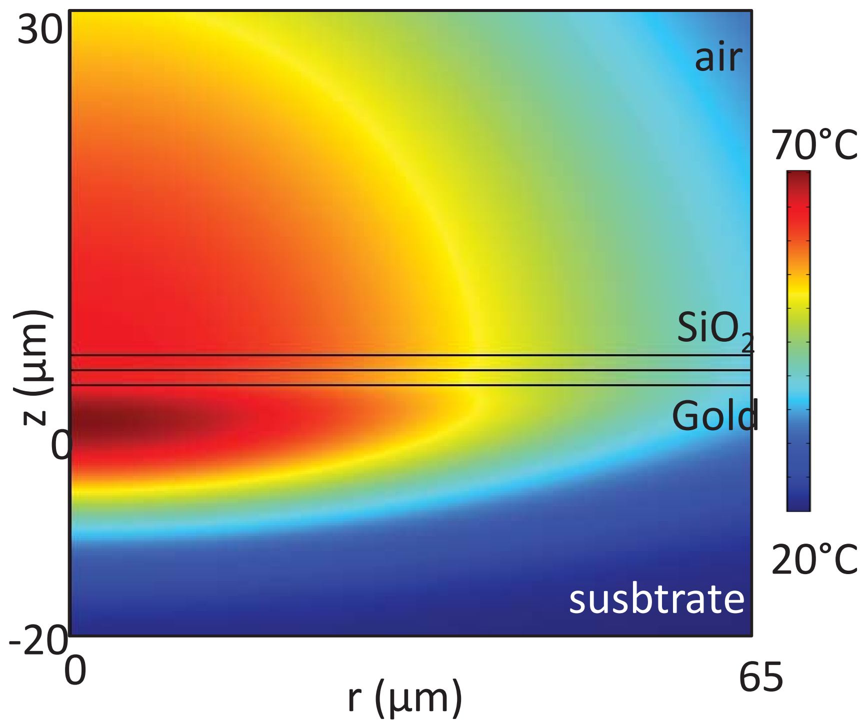
Decrease of the laser damage resistance under multiple pulses

SiO_2 single layer, 500fs, 1030nm, multiple shots at 10Hz (Fluence set to 70% of the single pulse threshold)

Basics of short pulse laser damage process

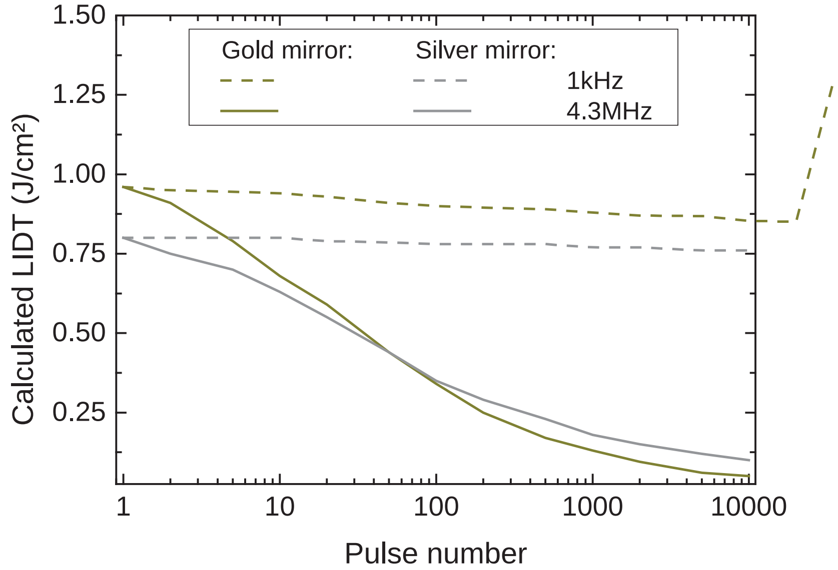
Thermal effects under multiple pulses

Sub-ps Laser irradiation can locally heat the materials



*Finite-element simulations of the temperature rise of a protected gold mirror 2µs after a 1 J/cm2, 90 fs, 800 nm, 10µm diameter pulse**

Heat can accumulate if the component does not have time to cool between two pulses



*Fluence needed to reach the melting point metallic mirrors at 1 kHz and 4.3 MHz repetition rates**

*B. Nagy et al., Opt. Lett. 40, 2525 (2015)

Outline

Basics of short pulse laser damage process

Damage resistance of optical materials

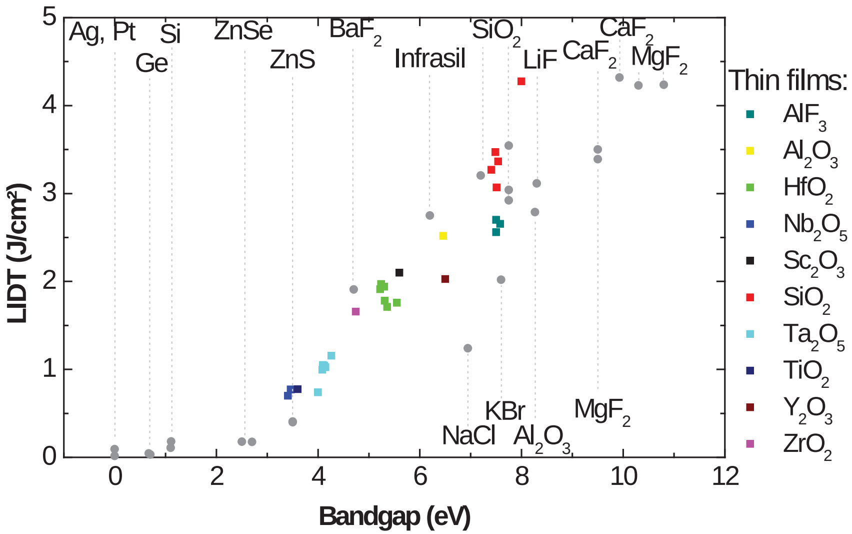
Damage initiation on defects

Improvement of laser damage resistance

Damage resistance of optical materials

Intrinsic Laser-Induced Damage Threshold

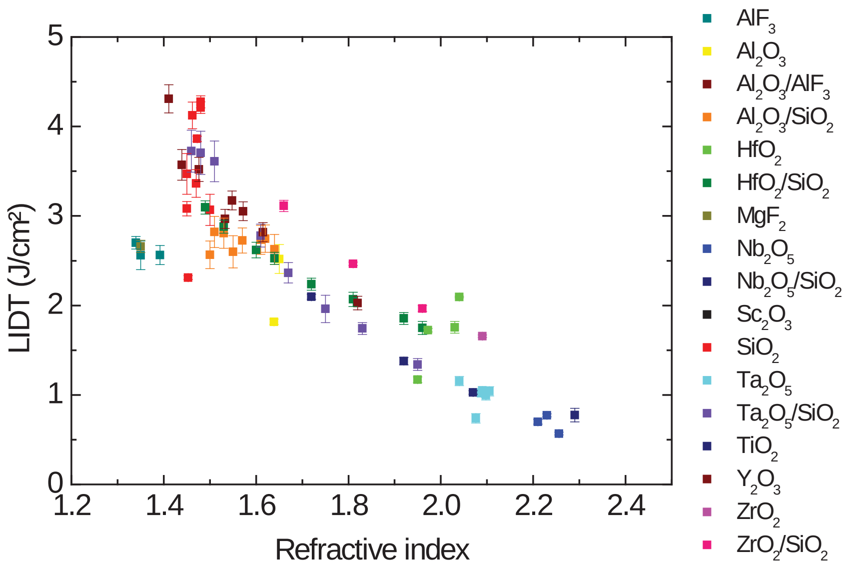
Direct dependence of LIDT on the material bandgap



*LIDTs of optical materials tested in single-shot at 500 fs and 1030 nm as a function of the measured optical bandgaps**

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

Clear correlation between the refractive index and LIDT



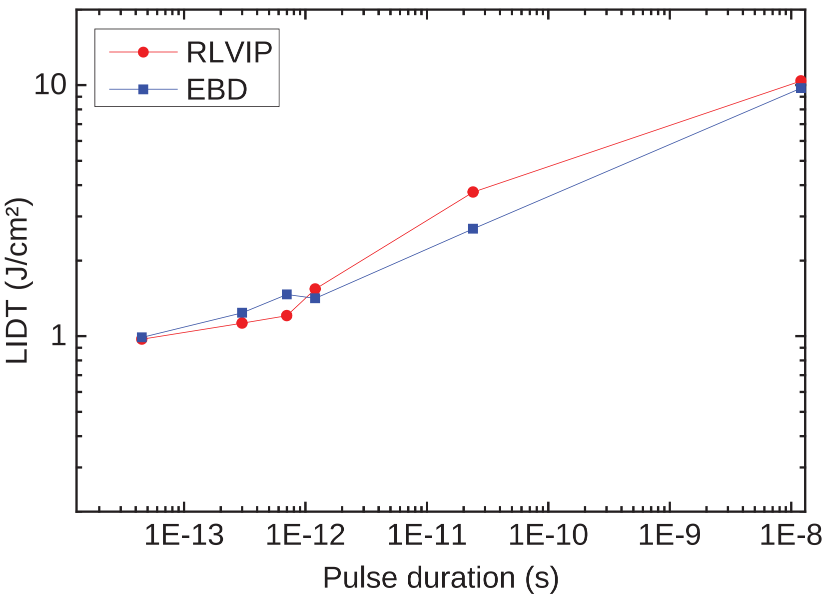
*LIDTs of optical thin film materials as a function of refractive index at 1030nm***

**B. Mangote et al., Opt. Lett. 37, 1478 (2012)

Damage resistance of optical materials

Parametric dependence

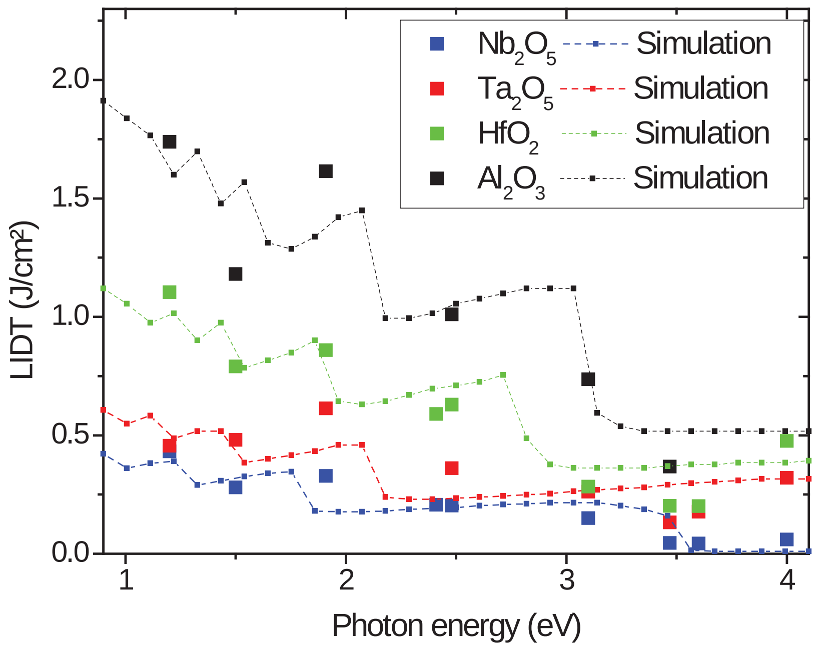
LIDT decreases with pulse duration for dielectrics



*LIDT of HfO_2 single layer coatings made by Reactive Low Voltage Ion Plating or Electron Beam Deposition as a function of pulse duration, tested at 1030/1064nm**

*L. Gallais et al., Appl. Opt. 50, C178 (2011)

LIDT decreases with wavelength



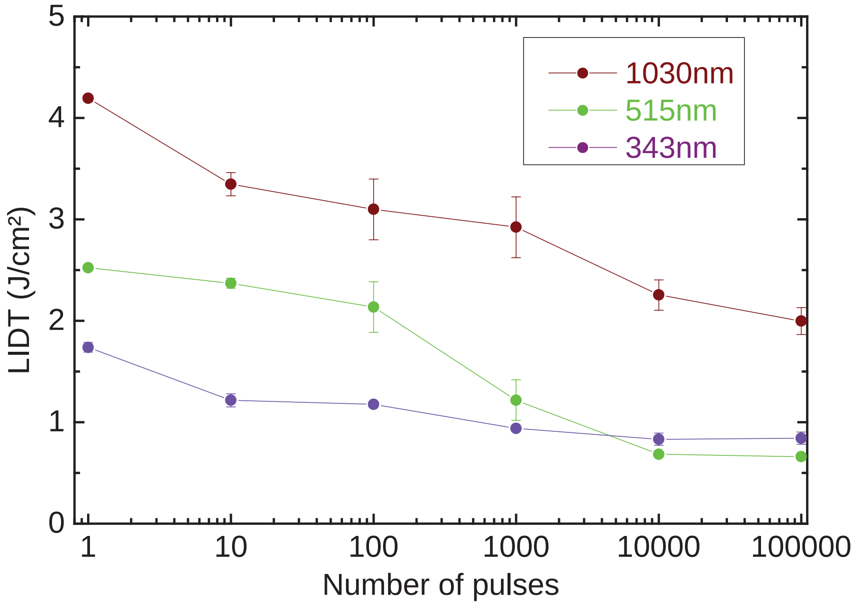
*LIDT at 100fs as a function of photon energy for different single layer coatings***

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

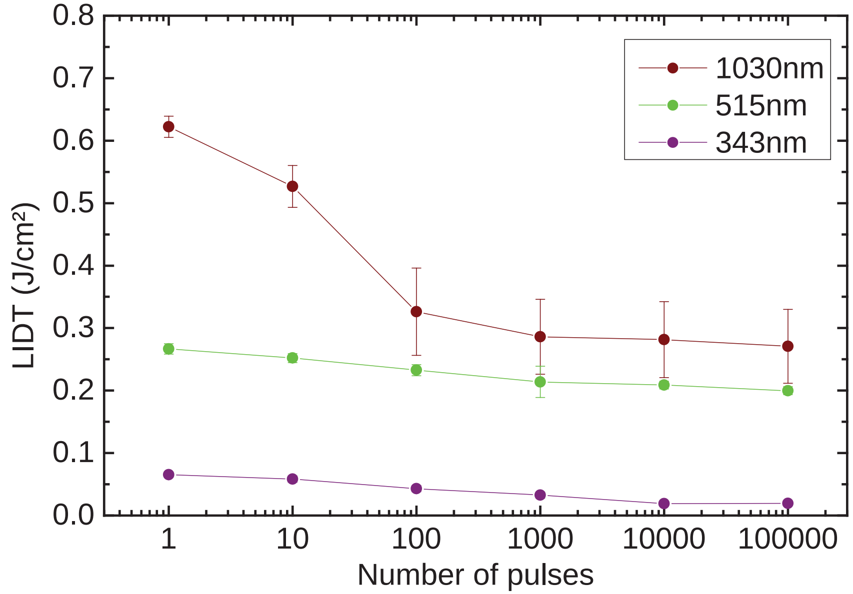
Damage resistance of optical materials

Multiple pulses

Excitations of mid-gap defect states at the microscopic level takes place under multiple irradiations, leading to a decrease of LIDT with increasing pulse number. This effect is strongly dependent on laser irradiation conditions and material



*Evolution of the LIDT with the number of pluses at 500fs for Silica film deposited by Magnetron Sputtering**



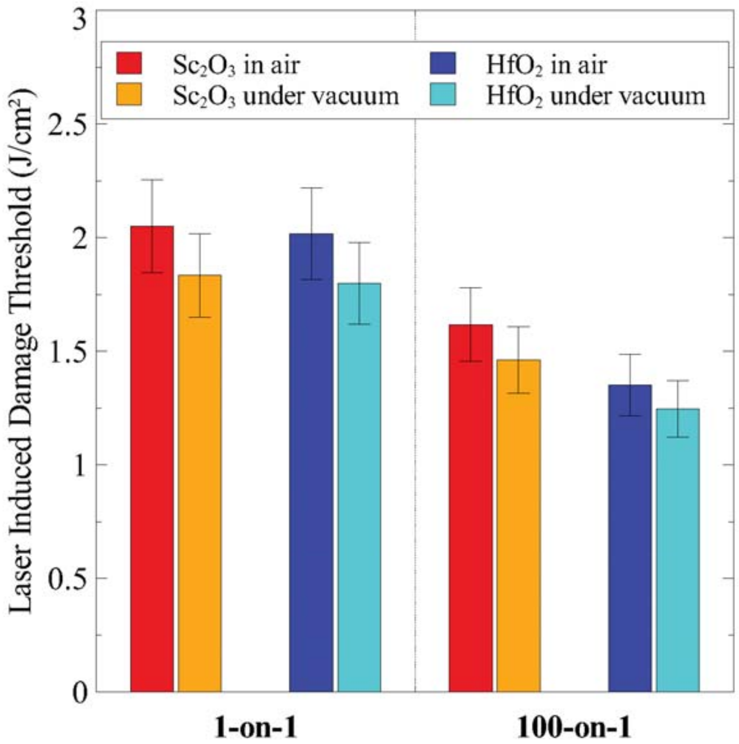
*Evolution of the LIDT with the number of pluses at 500fs for Niobia film deposited by Magnetron Sputtering**

*D.B. Douti et al., Opt. Eng. 53, 122509 (2014)

Damage resistance of optical materials

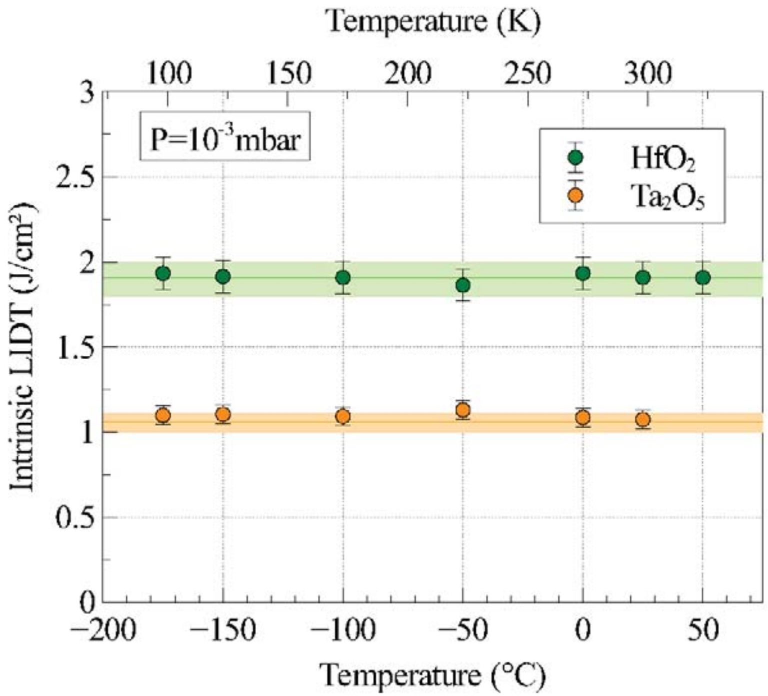
Environnemental conditions

LIDT decrease with pressure is observed for oxides



*LIDT of Hafnia and Scandia at 1030nm, 500fs, in air and under vacuum (10^{-3}mbar)**

No dependence with temperature is observed for cryogenic conditions



*LIDT (1030nm, 500fs) of dielectrics materials under vacuum at different temperatures**

*A. Hervy et al., Opt. Eng., to be published

Outline

Basics of short pulse laser damage process

Damage resistance of optical materials

Damage initiation on defects

Improvement of laser damage resistance

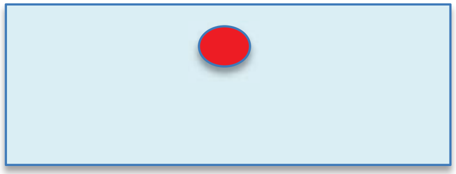
Sub-ps damage initiation on defects

Physical process

fs ps ns µs time

Sub-ps pulse

ns pulse



Localized absorption of laser radiation

- -Free electron absorption
- -Photo-ionization
- -Electron dynamics
- -Non linear absorption
- -E-field distribution effects

Energy transfer to host material

- -electron/phonon relaxation thermal conduction and radiation
- -plasma ball formation
- -avalanche ionization
- -melting, vaporisation
- -laser driven absorption

Mechanical & Hydrodynamic effects

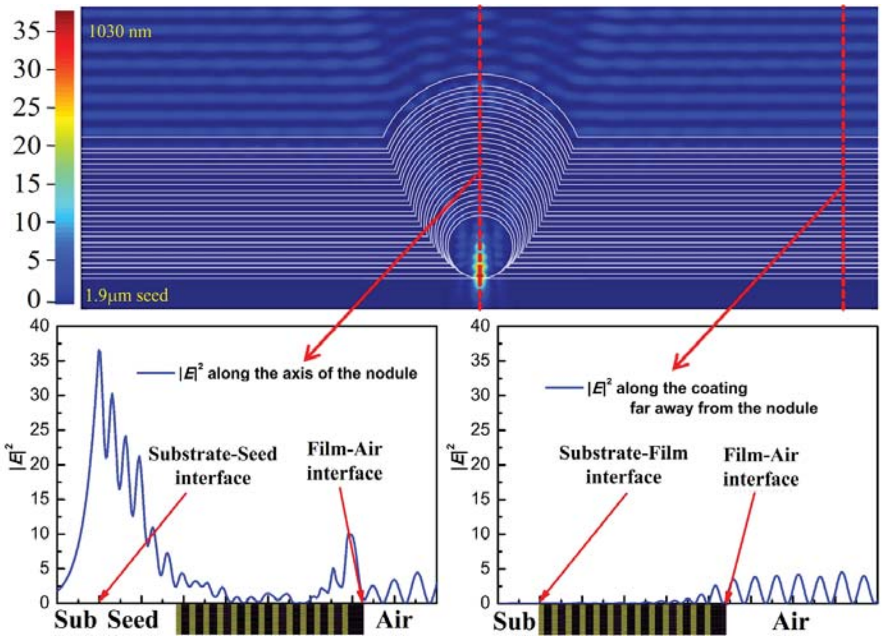
- -high internal pressure,
- -thermomechanical stress
- -shock wave
- -spalliation
- -fragmentation
- -ejection

Small precursors can initiate a cascade of events that can result in a macroscopic damage

Sub-ps damage initiation on defects

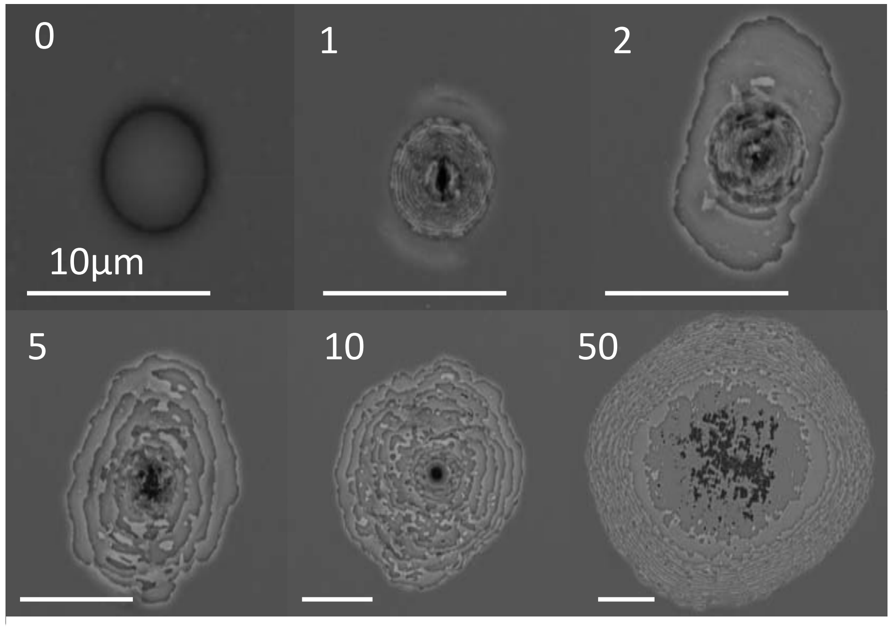
Defect initiation

Macroscopic defects can induce strong local intensity enhancement



*FDTD simulations of $|E|^2$ distributions for a nodular defect in a HfO_2/SiO_2 HR mirror**

Local reduction of damage threshold is observed on nodular defects



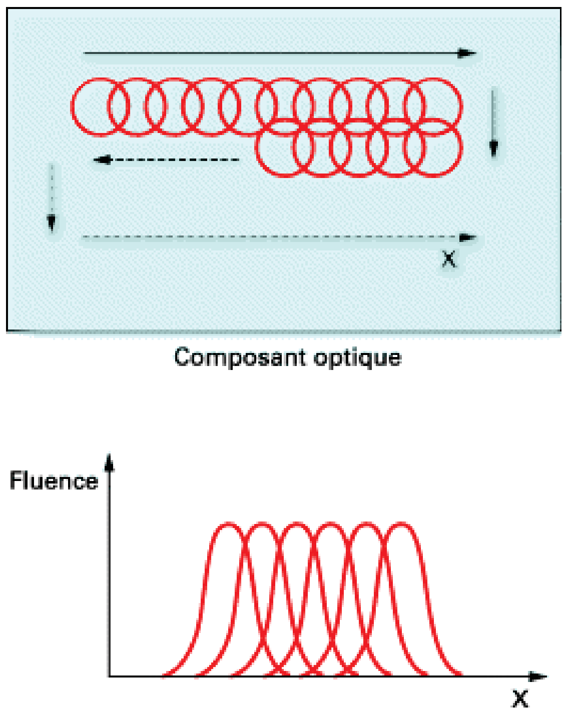
*Damage initiated by a nodular defects on a HR mirror under successive irradiations at 1.45 J/cm ^{2}.**

*L. Gallais et al., Opt. Lett. 39, 1545 (2014)

Sub-ps damage initiation on defects

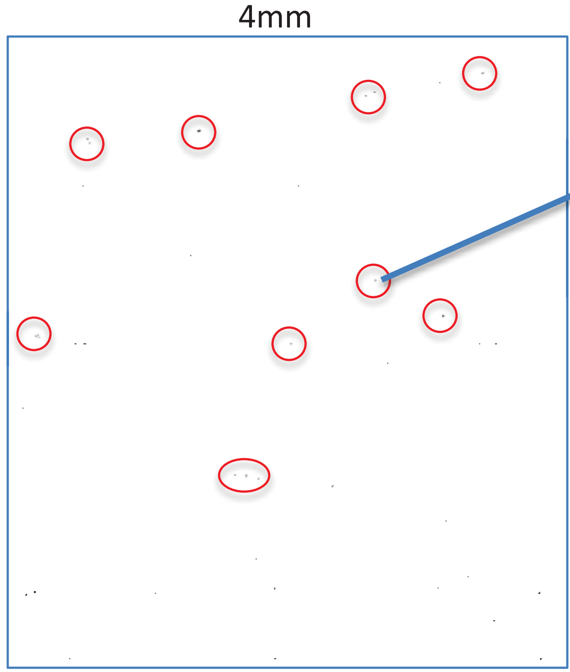
Damage densities

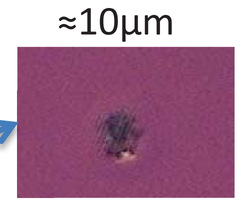
Specific damage test procedures can be applied to quantilfy limiting defects (damage densities / fluence)



Schematic description of a Raster scan test

Isolated damage events related to defects can occur for fluences significantly lower than the “intrinsic” LIDT





- 1on1 LIDT≈**0.8J/cm²**
- Raster scan ≈ **100 damages/cm² @0.4J/cm²**

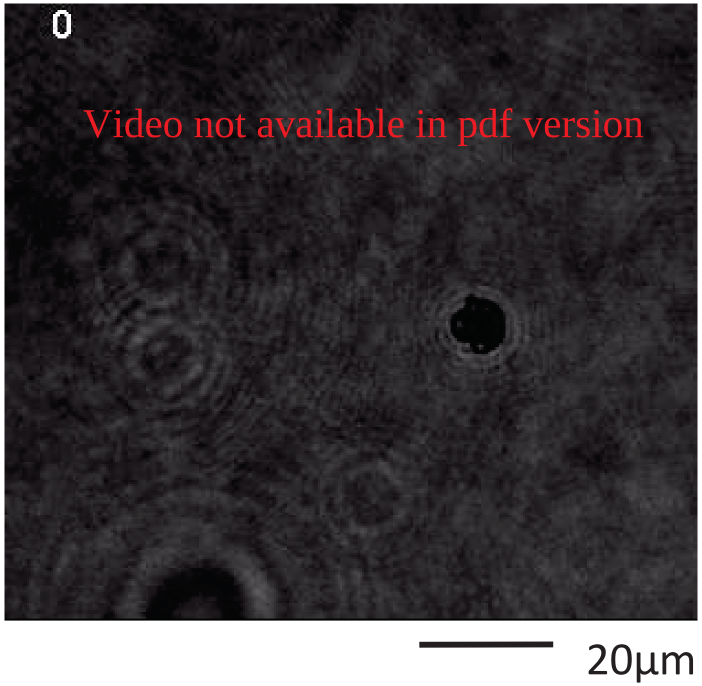
Damage sites revealed by a Raster scan test on a HR MMLD mirror (1030nm, 1ps)

Sub-ps damage initiation on defects

Damage growth

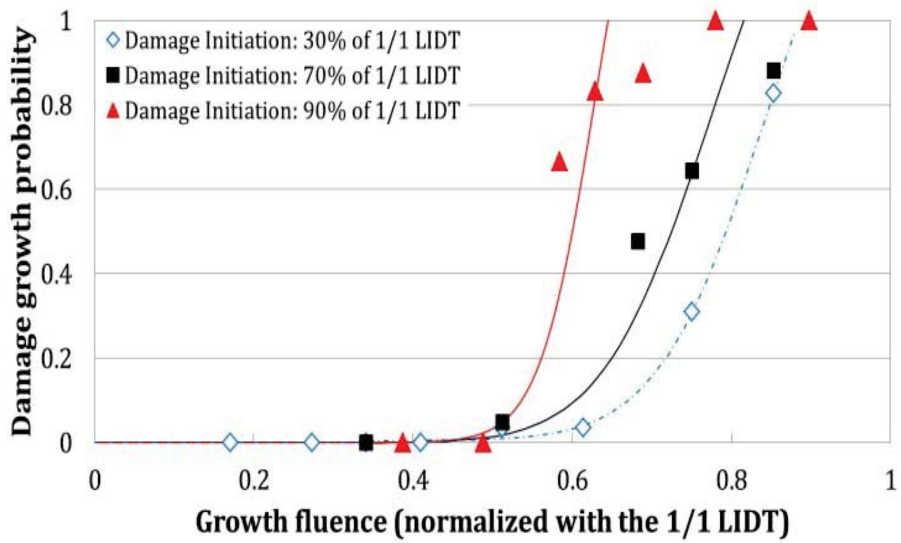
Once damage site is initiated, catastrophic damage growth limits the optics lifetime

Growth can be triggered for fluences as low as 50% of the intrinsic damage threshold of the component.



*Sequence of shots on a defect-initiated damage, at a fluence set to 60% of the single pulse LIDT**

*M. Sozet et al., Opt. Lett. 41, 2342 (2016)



*Evolution of the probability of growth as a function of fluence (normalized with respect to the single pulse LIDT). HR mirror, 45°, P, 1030nm, 1ps. **

Outline

Basics of short pulse laser damage process

Damage resistance of optical materials

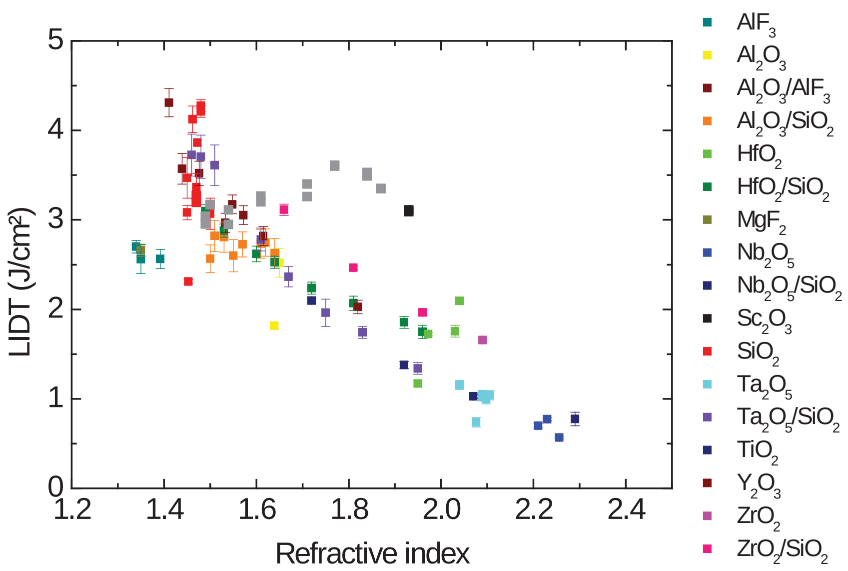
Damage initiation on defects

Improvement of laser damage resistance?

Improvement of laser damage resistance

Materials & manufacturing

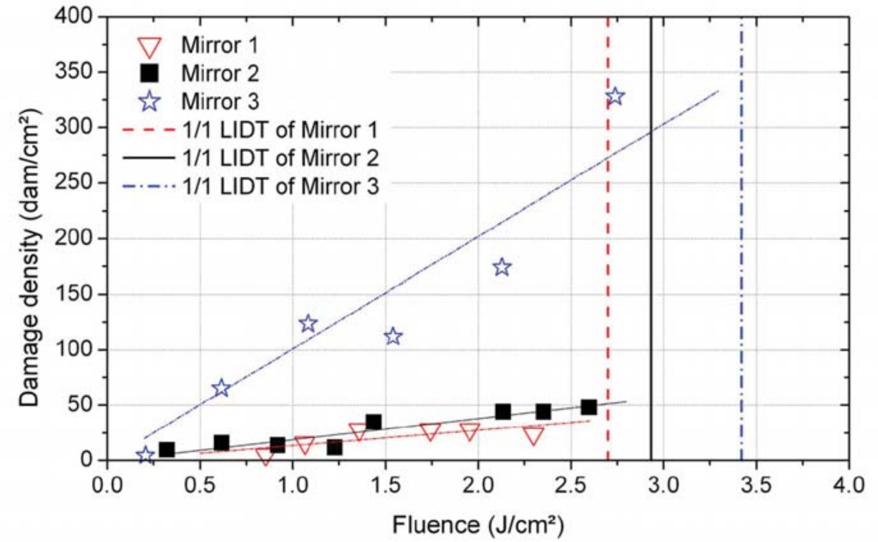
Engineered materials such as binary mixtures are interesting combinations for interference coatings used in high-power applications



*LIDT of IBS Sc_2O_3/SiO_2 mixtures compared to other coating materials**

*M. Mende et al., Appl. Opt. 52, 1368 (2013)

Reduction of defect densities related to the manufacturing process



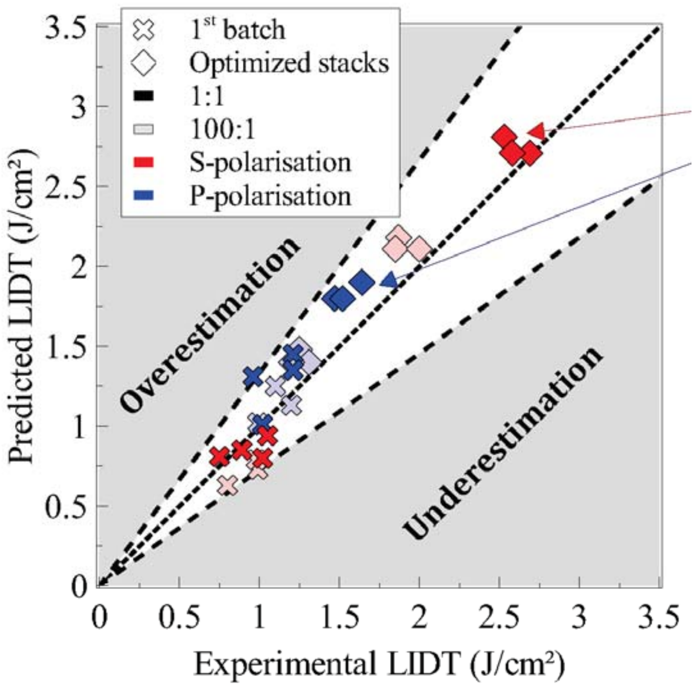
*Raster scan and 1on1 measurements on different HR mirrors (1053nm, 675fs, 45° AOI, P polar)**

*M. Sozet et al., Opt. Lett. 40, 2091 (2015)

Improvement of laser damage resistance

Optimization of E-field distribution

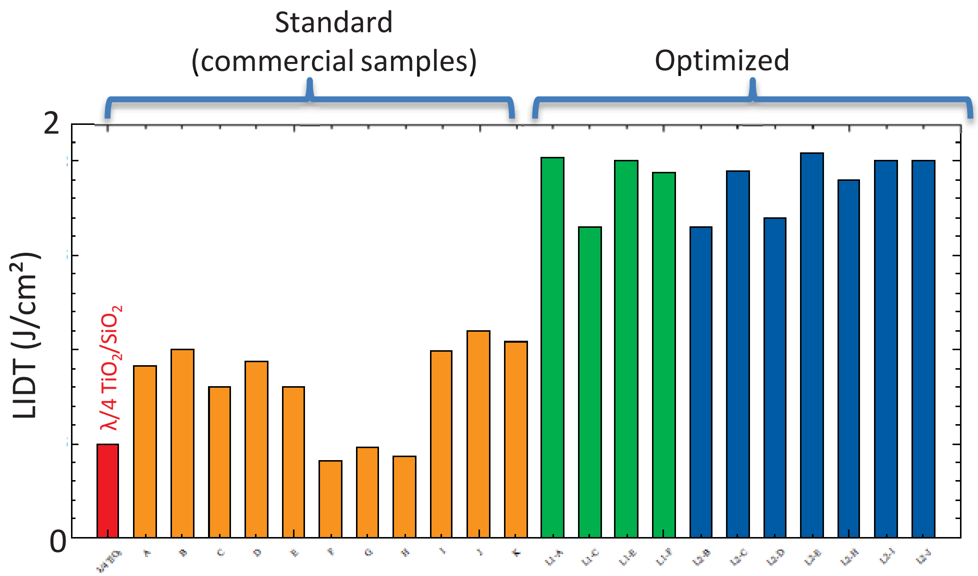
The theoretical LIDT of a component can be obtained from the knowledge of the E-field distribution and LIDT of materials



*Optimization of 45° broadband HR-coatings.for Appolon 10PW laser project**

*A. Hervy et al., Opt. Eng., to be published

Significant improvement can be obtained with optimization of the E-field distribution



LIDT of broadband reflective mirrors :R>99%, Δλ>250nm (S) / 160nm (P)

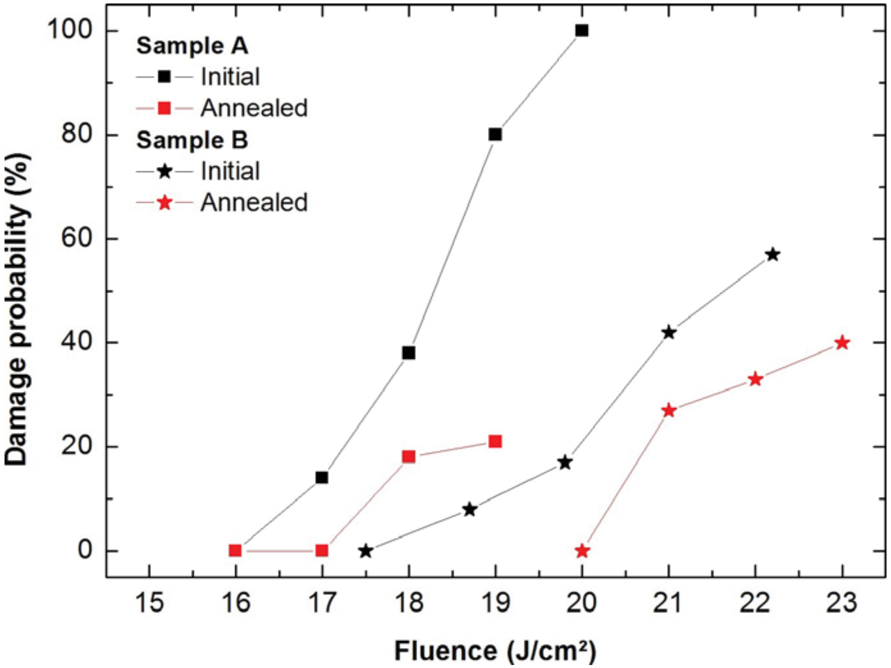
*Tests at 800nm, 40fs, 5kHz***

**A. Hervy, PhD thesis, 2016

Improvement of laser damage resistance

Post processing

Laser conditioning or thermal annealing can significantly enhance the LIDT



*Improvement of LIDT on the surface of fused silica optis at 355nm, 3ns, with isothermal annealing at 1050°C for 12h**

*T. Doualle et al., J. Appl. Phys. 119, 213106 (2016)

Specific treatments can mitigate (arrest) laser damage growth

*Example of CO_2 laser processing of damage on fused silica for the Laser MegaJoule project**

*T. Doualle et al., Submitted

Conclusions

The physics of laser damage in the sub-picosecond regime is quite well understood

Intrinsic performances of optical materials can be ranked based on their bandgap and scaling laws can be derived

Consequently theoretically high laser damage threshold optics can be designed based on available materials

However for applications two main points need to be considered and deeply studied:

- ‘Incubation’, ‘fatigue’ or heat accumulation effects of the materials under multiple pulses
- The densities of growing damage sites related to manufacturing defects and/or contamination

Post processing techniques that have been applied in the ns regime (annealing, laser conditioning, damage growth mitigation,etc..) could also be of potential interest

Thank you for your attention!

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