Nanosecond laser induced damage in nonlinear optical crystals

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Introduction

Laser induced damage in optical materials

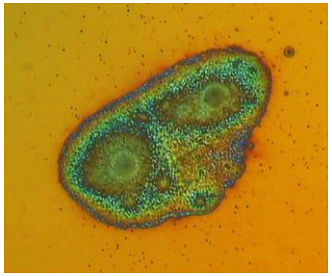
Optical materials are usually *transparent* → There *should* be no energy deposition, no damage

However …

Multi-photon absorption → Absorption at high intensities

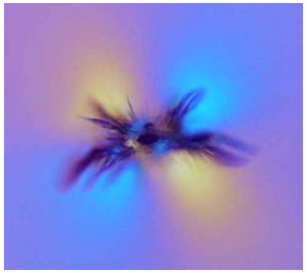
Small defects (< 1µm) or defect clusters → Locally high absorption

… Laser damage appears



On coatings

In the bulk

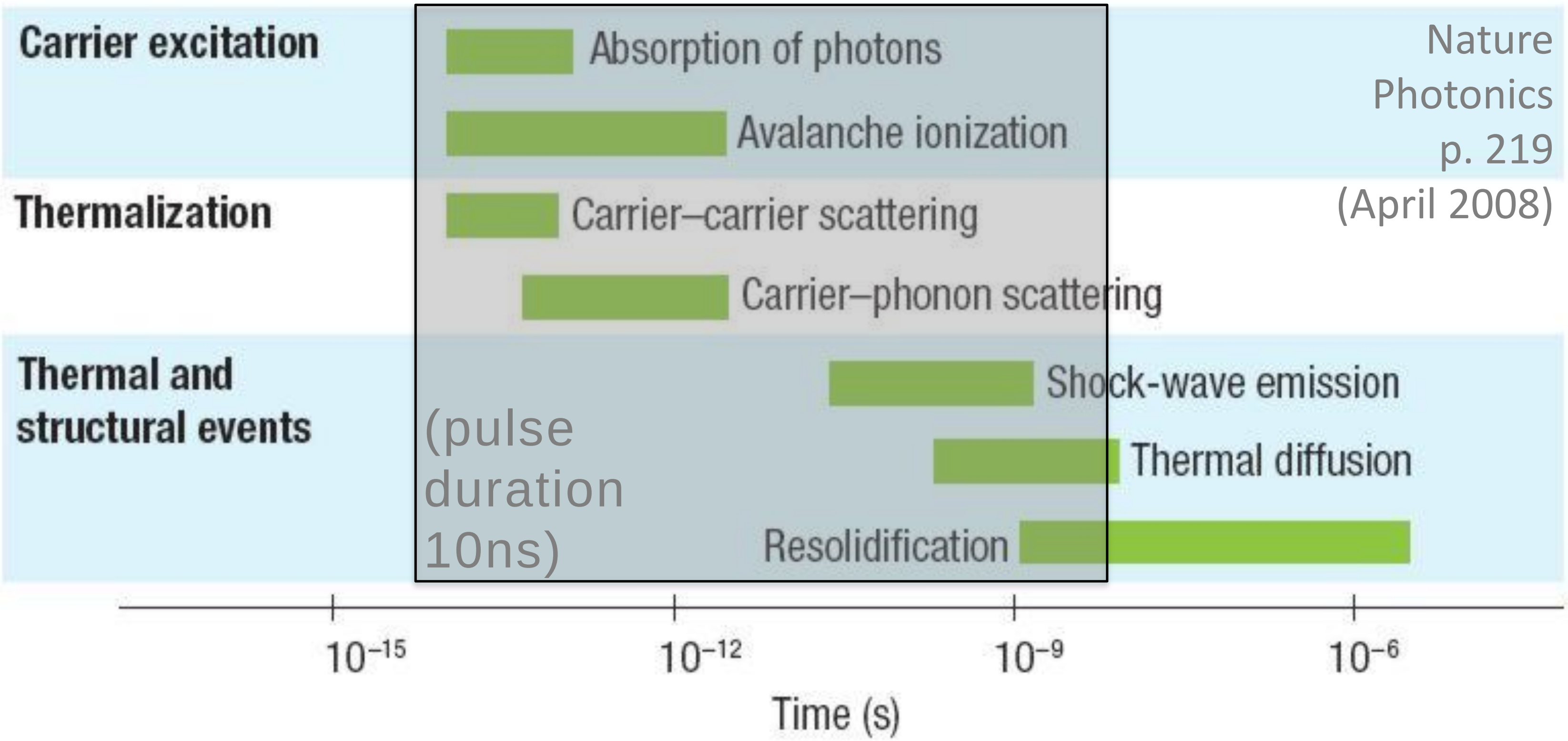


Typical size at initiation: <100 µm

(any beam size)

Introduction

Overview of the underlying physical processes

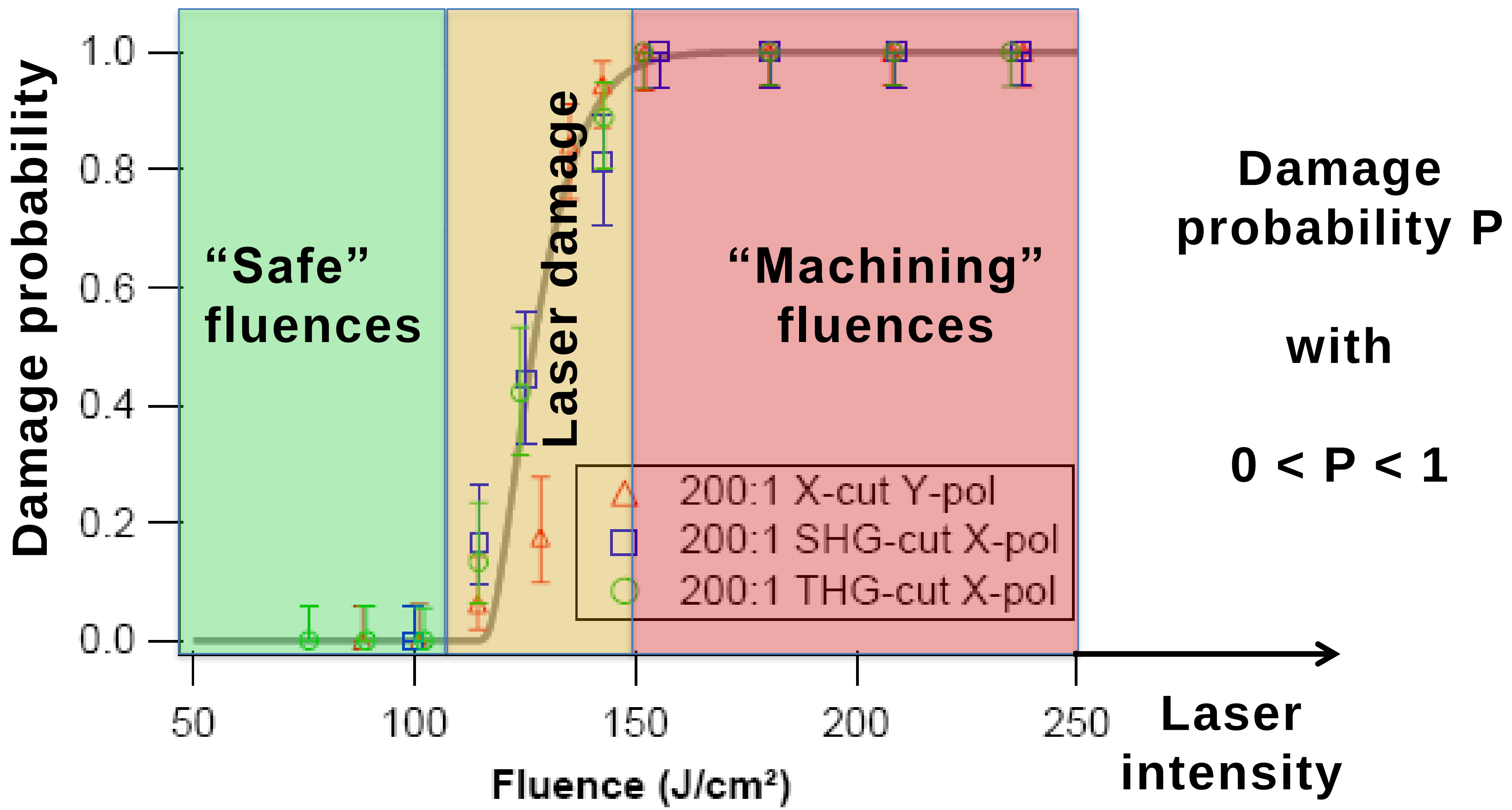


Nature Photonics p. 219 (April 2008)

- Complex interplay of different physical mechanisms
- Different weights for different materials or lasers

Introduction

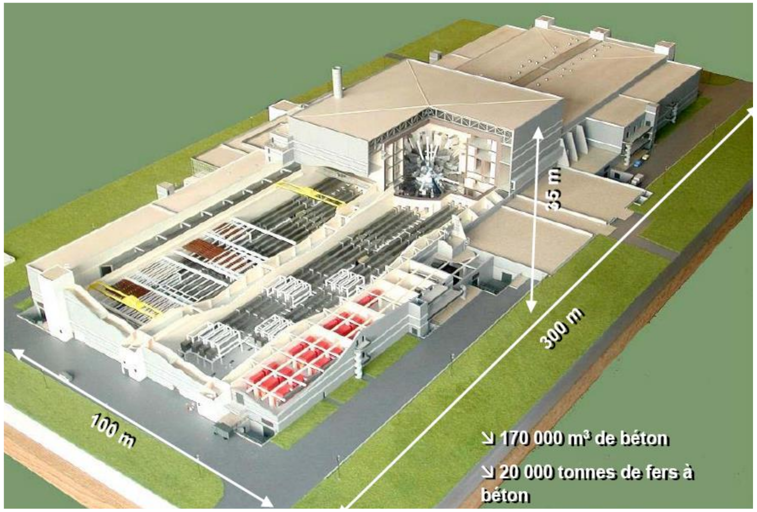
Laser damage studies vs. laser machining



Nanosecond laser damage: *Non-deterministic* (**statistic**) interaction between material and high power light.

Introduction

The role of laser damage studies in important projects

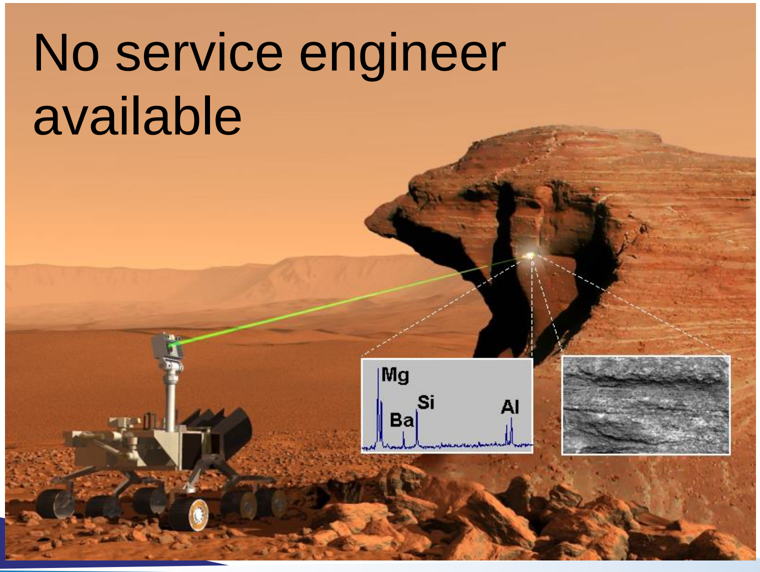


Laser Megajoule, Bordeaux, France

Needs: *high single pulse thresholds* on *large surfaces*

Lens size: 40cm x 40cm

1053nm: 25J/cm^2; 351 nm: 14J/cm^2



CHEMCAM instrument, Mars Science Laboratory

Needs: low weight and *long life-time in harsh environment*

LIBS at a distance of 7 m

1067nm, -30°C -> +60°C,

Introduction

Fields of activity

Our task

- **Describe the effects:**
  depending on parameters like:
  energy density (fluence, J/cm^2) and pulse number
- **Quantify the risk**:
  measure damage probabilities, thresholds, growth coefficients…
- **Understand** what happens

Our 'clients'

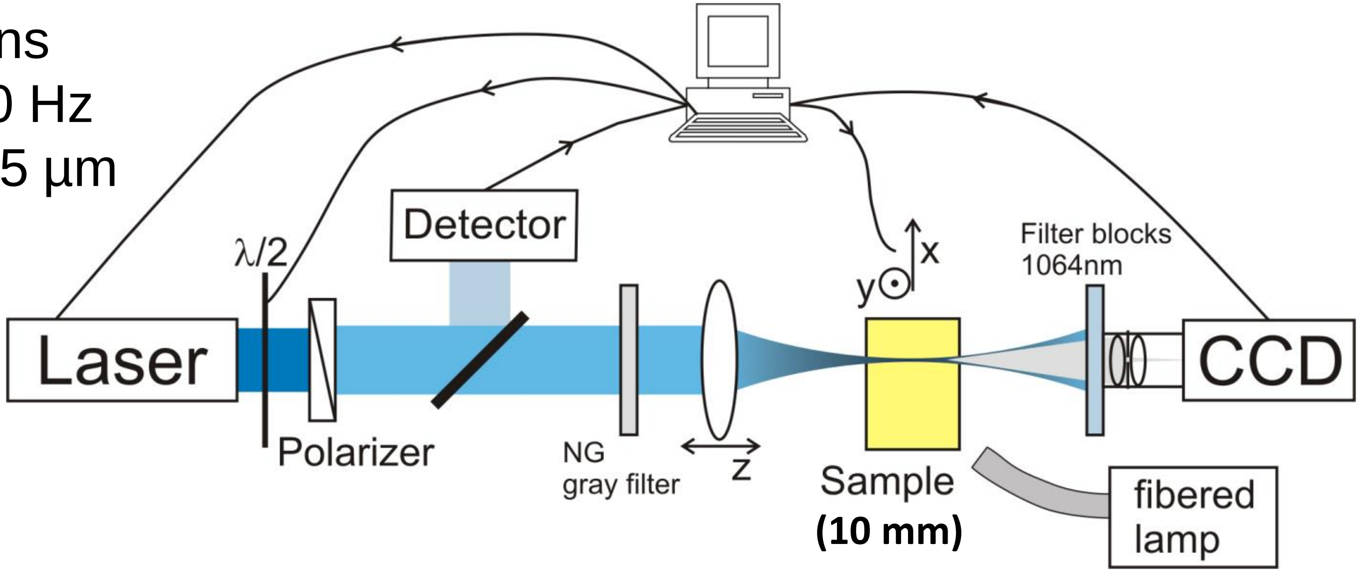
- **High power photonics designers:**
  - Choose the best provider
  - Make 'sure' things will work as they should
- **Component manufacturers:**
  - See if your new component is better

Quantifying laser damage

A typical testing setup

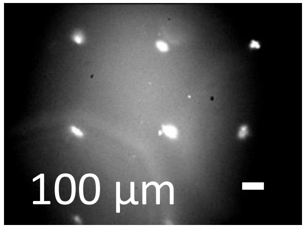
Laser

λ = 1064 nm
pulse duration: 6 ns
pulse rep. rate: 10 Hz
beam diameter: 75 µm

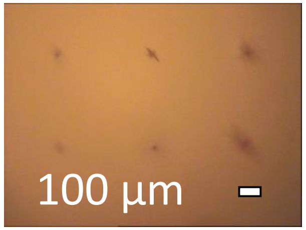


Damage detection

Imaging of scattered light:



Scattered light



Ex situ microscope

Quantifying laser damage

The multi-pulse "S-on-1" test procedure

A test procedure close to real life:

- Constant fluence ***F***
- Up to ***S*** pulses on one site
- Test some sites per fluence and estimate the damage probability ***P***

(***P*** = # broken / # tested)

- With online damage detection: Save the number of the damaging pulse, N_D, for each broken site.

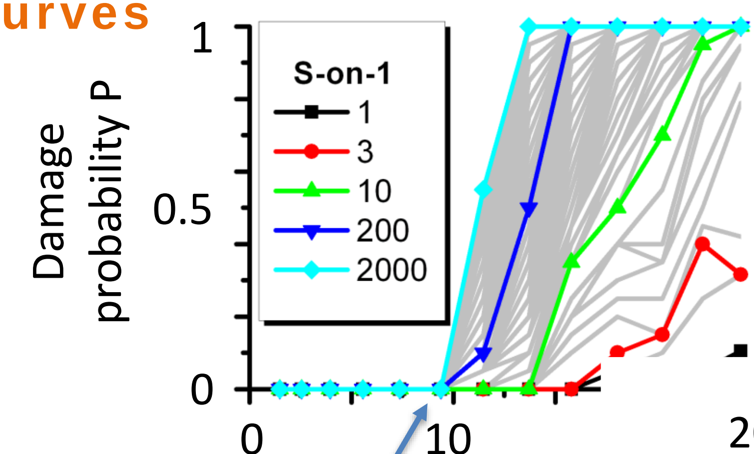
→ Any X-on-1 damage curve, with $1 \leq X \leq S$, can be extracted from this data

The “fatigue effect” and its interpretation

A definition

P(F,S) = Probability to fail, at fluence F, for S pulses or less

P(F) curves



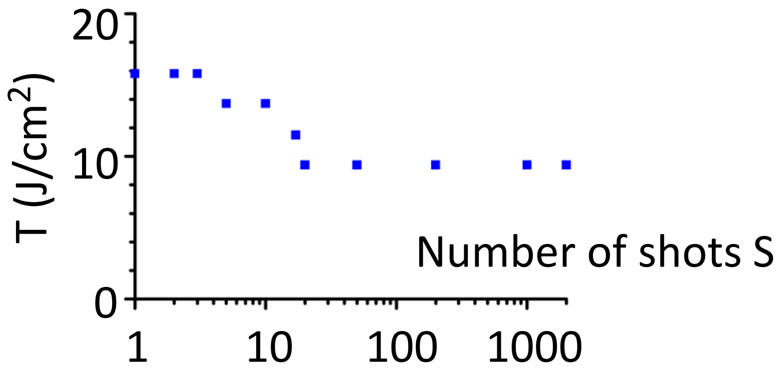
KTP, bulk

1064 nm, 6 ns

T(S) curves

S-on-1 damage threshold T

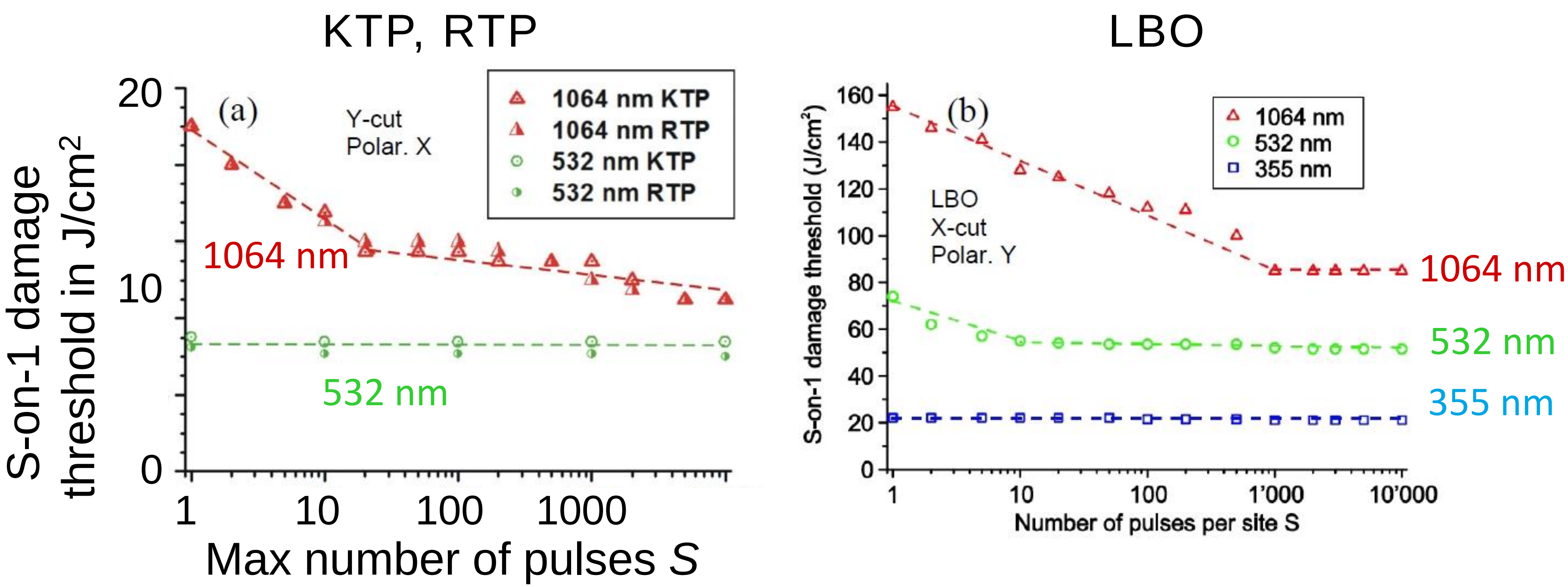
Here T(2000-on-1)



By definition, there is a “fatigue effect”, if T(S) decreases.

The “fatigue effect” and its interpretation

Threshold behavior in some NLO crystals



It is difficult to imagine a material modification that is caused by IR, but not by visible and UV light.

➡ Is there really a material modification necessary to understand IR fatigue?

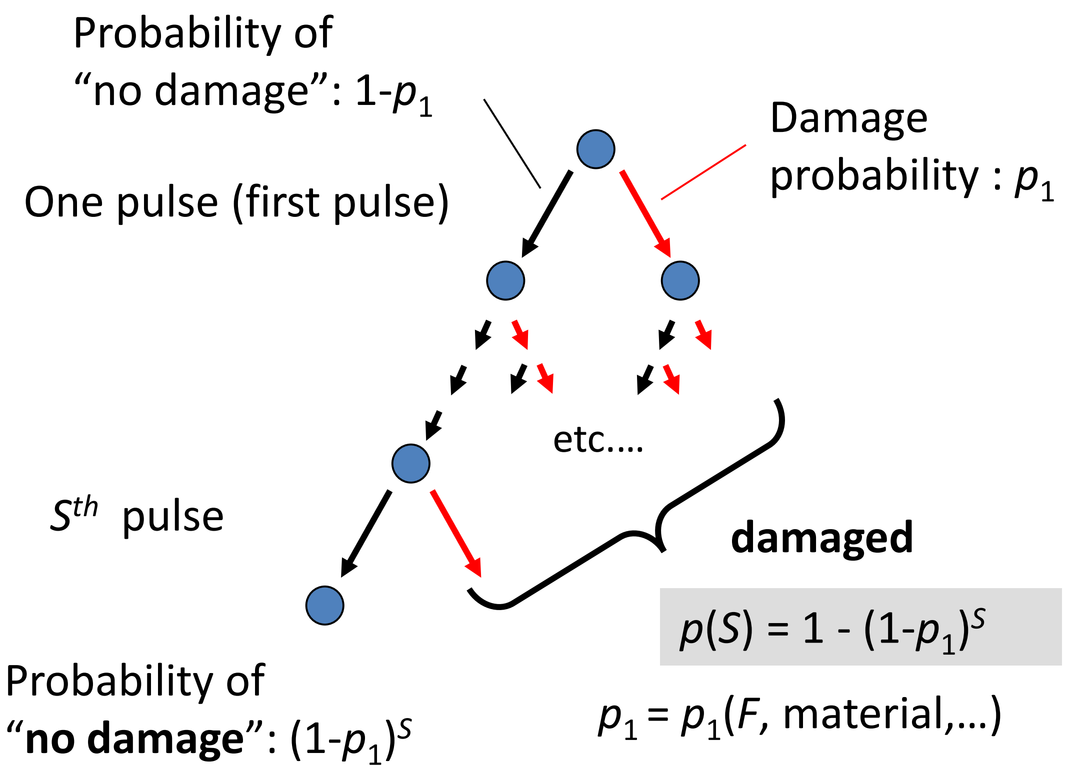
The "fatigue effect" and its interpretation

Ideas that do not suppose material modifications

Laser instability **Too small effect** for the bulk of KTP and our laser.

Statistically independent resampling

The single-pulse damage probability p_1 does NOT depend on the number of pulses (that the test site received before).



Multiple-pulse laser-induced damage

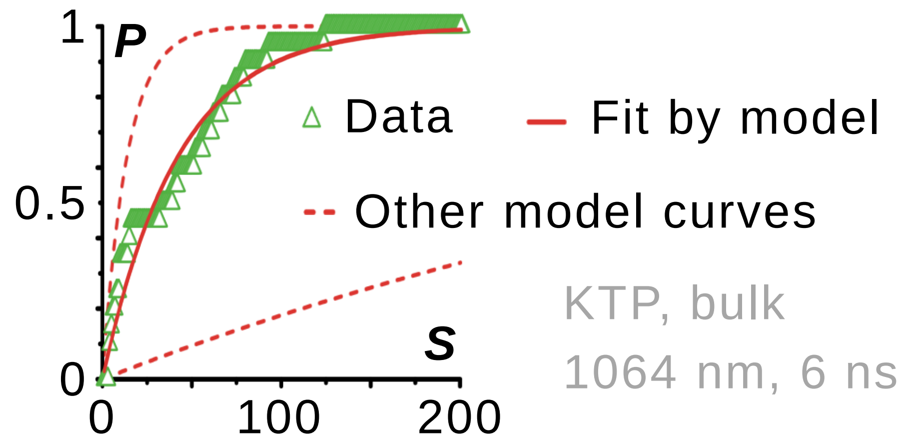
Two possible reasons for “fatigue”

Statistical effect

With <u>constant</u> single-pulse damage probability p_1:

$$P(S) = 1 - (1 - p_1)^S$$

for any given fluence.

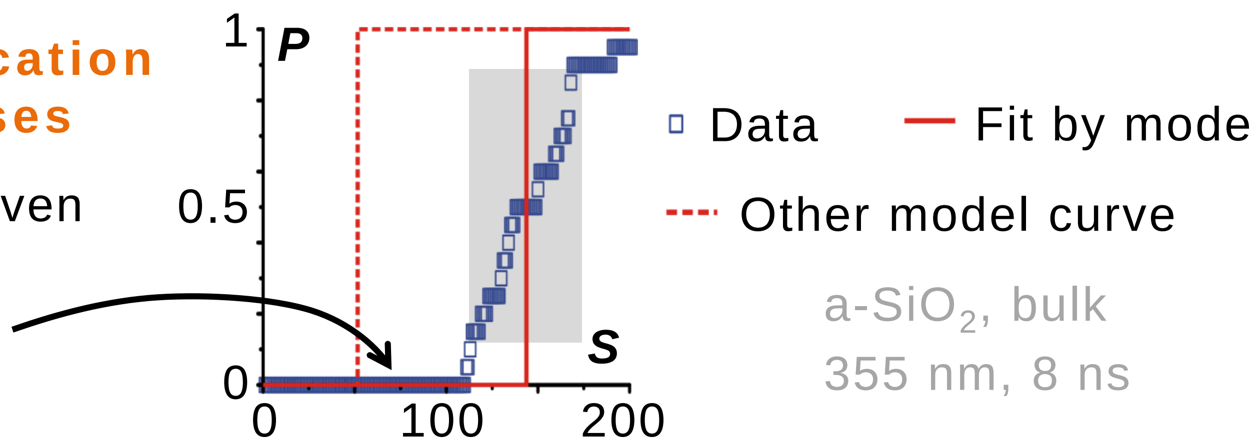


No material modification (pseudo-fatigue)

Material modification by the first pulses

Transition width given by laser stability

Incubation pulses



The damage mechanism in KTP and RTP

Different series of experiments

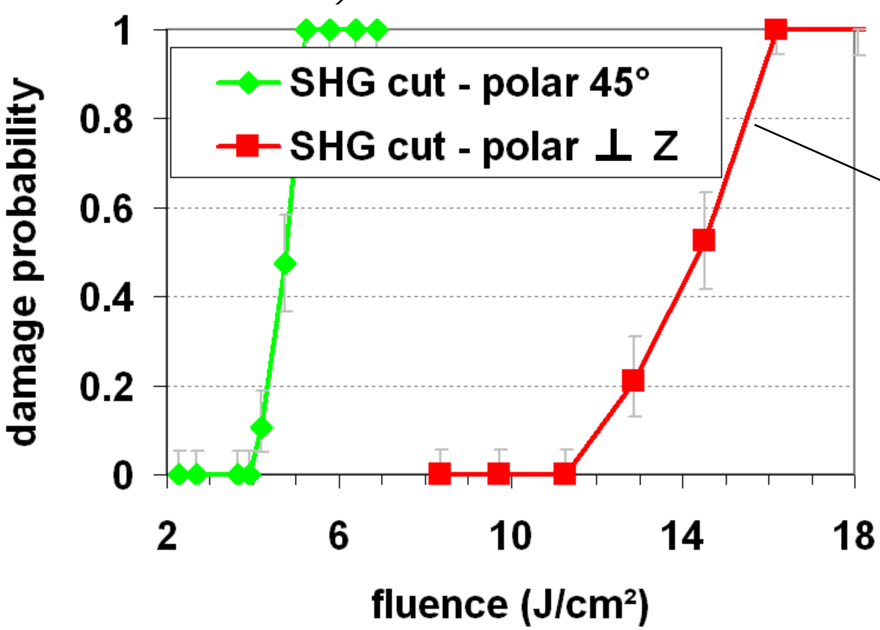
Series	Observations
Pulse number per site (S-on-1)	KTP = RTP : No material modifications revealed; statistical fatigue in the IR, no fatigue at 532 nm
Cristal quality (absorption and ionic conductivity)	RTP : No influence
Propagation direction and *polarization direction* (x, y, z)	KTP = RTP : Propagation dir. -> No influence (if no conversion) Polarization -> z-pol. is more resistant
Frequency conversion (SHG efficiency)	**KTP : less resistant to mixed exposure than to pure 532 nm exposure**

The damage mechanism in KTP and RTP

KTP - the influence of SHG

Doubling efficiency: 21%

(walk off)



Mismatch for type I SHG:
$\Delta k = 1.66\ 10^{4}\ cm^{-1}$

No green light

Cooperative damage mechanism
as already proposed by Favre *et al.** (µs-laser damage in KTP).

The presence of green light lowers the damage threshold of KTP dramatically

* IEEE J. Quant. Electr. (2003)

The damage mechanism in KTP and RTP

The physical model

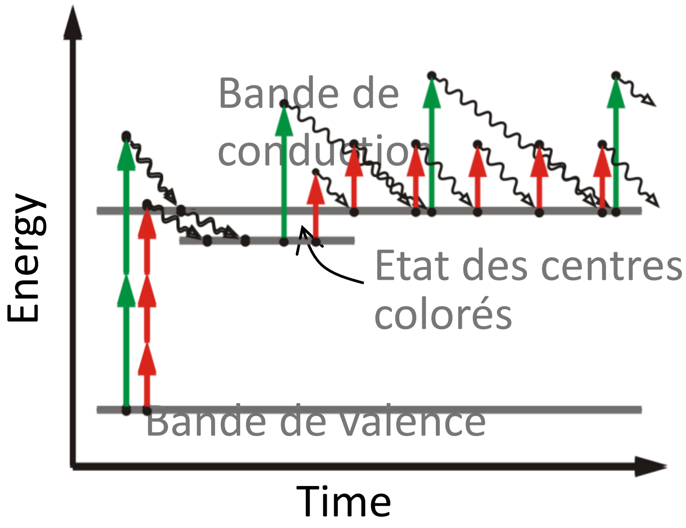
A good deal of **fundamental studies** exist on KTP:

- Intrinsic absorption if $h\nu \geq$ 3.50 eV.
- Material with strong photon-phonon coupling
- Generation of unstable color centers is possible
- 270 cm^{-1} phonons destabilize the color centers

➡ Quantitative formulation using RATE EQUATIONS on the transitions per time and volume

Step 1 : Generation of unstable excited states (may relax to color centers)

Step 2 : Heating of electrons in the conduction band



Electron relaxations are associated with emissions of phonons

Summary and conclusions

Laser damage tests are mandatory for certain high power photonics projects

Nonlinear optical crystals (KTP, RTP)

- *Several systematic measurement series are necessary to develop a model for the physical processes leading to damage.*
- *Nanosecond laser damage can be intrinsic.*
- *Simultaneous presence of different wavelengths can cause strong cooperative effects.*

Thin films

- *For large beams, fabrication defects cause laser damage (no fatigue).*

Acknowledgements

Thank you for your attention