Sapphire and titanium-doped sapphire crystals under nanosecond and femtosecond laser irradiation

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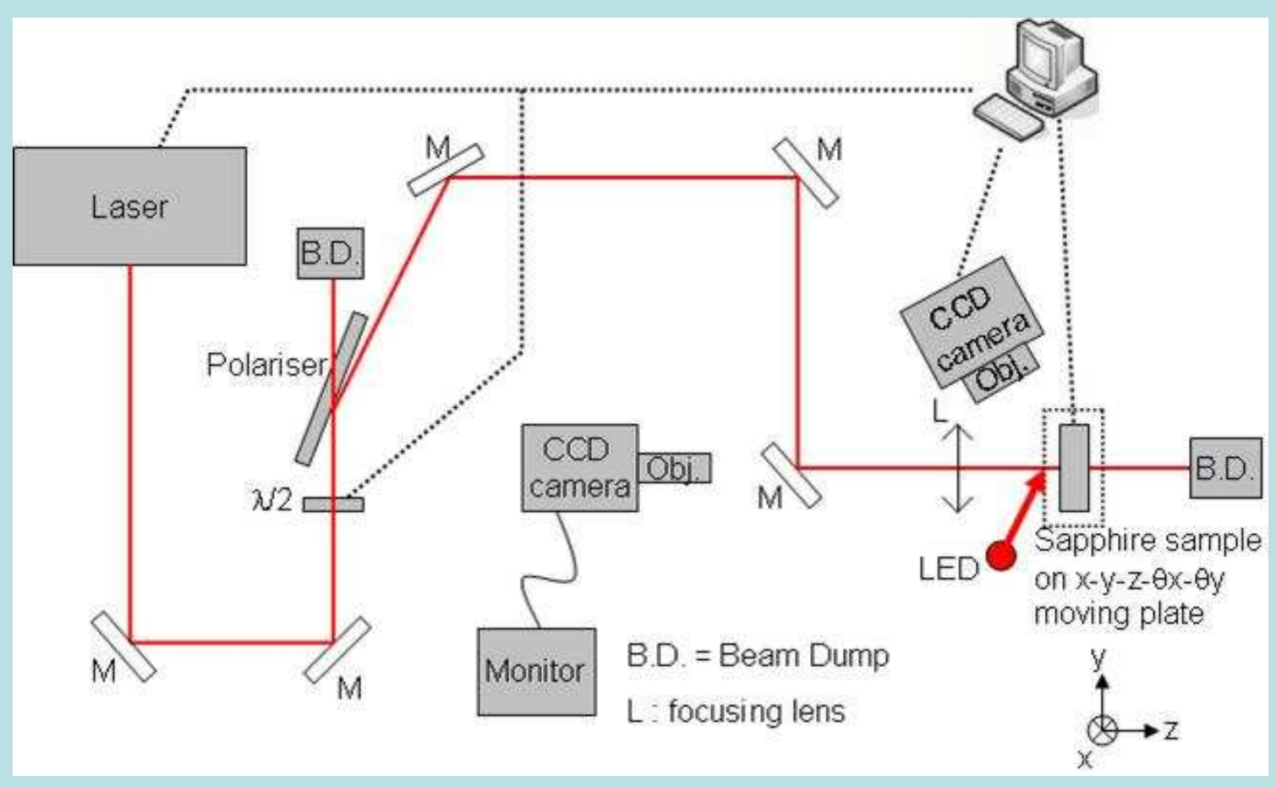
Abstract

In the framework of high peak power laser technology, this work aims to quantify the laser damage threshold of monocrystalline sapphire and titanium-doped sapphire in various temporal regimes (ns and fs), representative of different laser-matter interaction modes. The importance of various beam parameters such as polarization, pulse duration, beam size and number of shots is investigated. We also consider the influence of doping and surface polishing on the laser-induced damage threshold (LIDT) of the material. The results are important to identify the key mechanisms leading to laser damage and help to define the optimal strategy of crystal illumination (laser pumping) for safe and robust operation of high peak-power laser systems.

Experimental set-up, damage detection



Laser	Wavelength	Pulse duration FWHM	Maximum Energy - Repetition rate	Rms stability	Beam waist and M^2
Amplitude Systèmes “S-pulse”	1025 nm	450 fs	200µJ 1kHz	2%*	10.8 µm $M^2 \approx 1.3$
Quantel “Ultra GRM”	532 nm	7 ns	30mJ 10Hz	2%	5.4 µm $M^2 \approx 1.3$

* ~8%when operated with external trigger(single shot).

The same set-up configuration, test procedure, samples and diagnostic tools were used for both fs and ns temporal regimes.

➢ **Test procedure:** [1]

a) 1(or N) shot(s) on 1 fresh site of the sample: 1on1(Non1) + Damage detection (Yes/No)
b) Step “a” repeated 30 times for each fluence ⇨ probabilistic study
NB: - Damage initiation is sensitive to peak fluence, given by $F=2E/(\pi\omega_0^2)$ [2]
- Damage = permanent material modification, visible by optical microscopy
- Threshold fluence F_{th} = highest fluence for which damage probability is zero

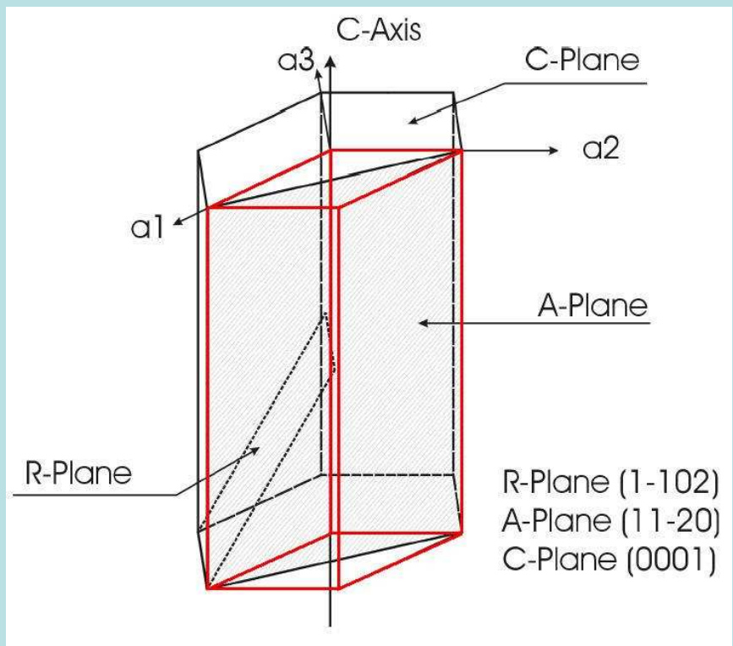
Note: In the following curves, the lines linking the points are shown to help guiding the eye.

➢ **3 kinds of samples are used for this study:**

Sample 1: Sapphire, c-axis perpendicular to face, classical polishing (Ra=1nm)
Sample 2: Sapphire, c-axis perpendicular to face, Ti:Sa–like polished (Ra=2nm)
Sample 3: Ti doped sapphire, c-axis parallel to face, Ti:Sa–like polished (Ra=2nm)

➢ **Diagnostic tools:**

- In-situ : Scattered light detection by CCD camera coupled with a telecentric objective & image subtraction
- Ex-situ : Optical microscope with x100 objective, AFM, SEM



➢ **Critical power for self focusing:** [3]

		Sapphire Bulk / Front face	Sapphire Rear face	Air
450fs	P_{cr}	**3,1 MW**	x	3,35 GW
	F_{cr}	**0,75 J/cm²**	x	820 J/cm²
7ns	P_{cr}	0,4 MW	0,4 MW	0,9 GW
	F_{cr}	6500 J/cm²	130 J/cm²	14 MJ/cm²

$$P_{cr} = \frac{3.77\times\lambda^2}{8\pi n_0 n_2^{i}}$$

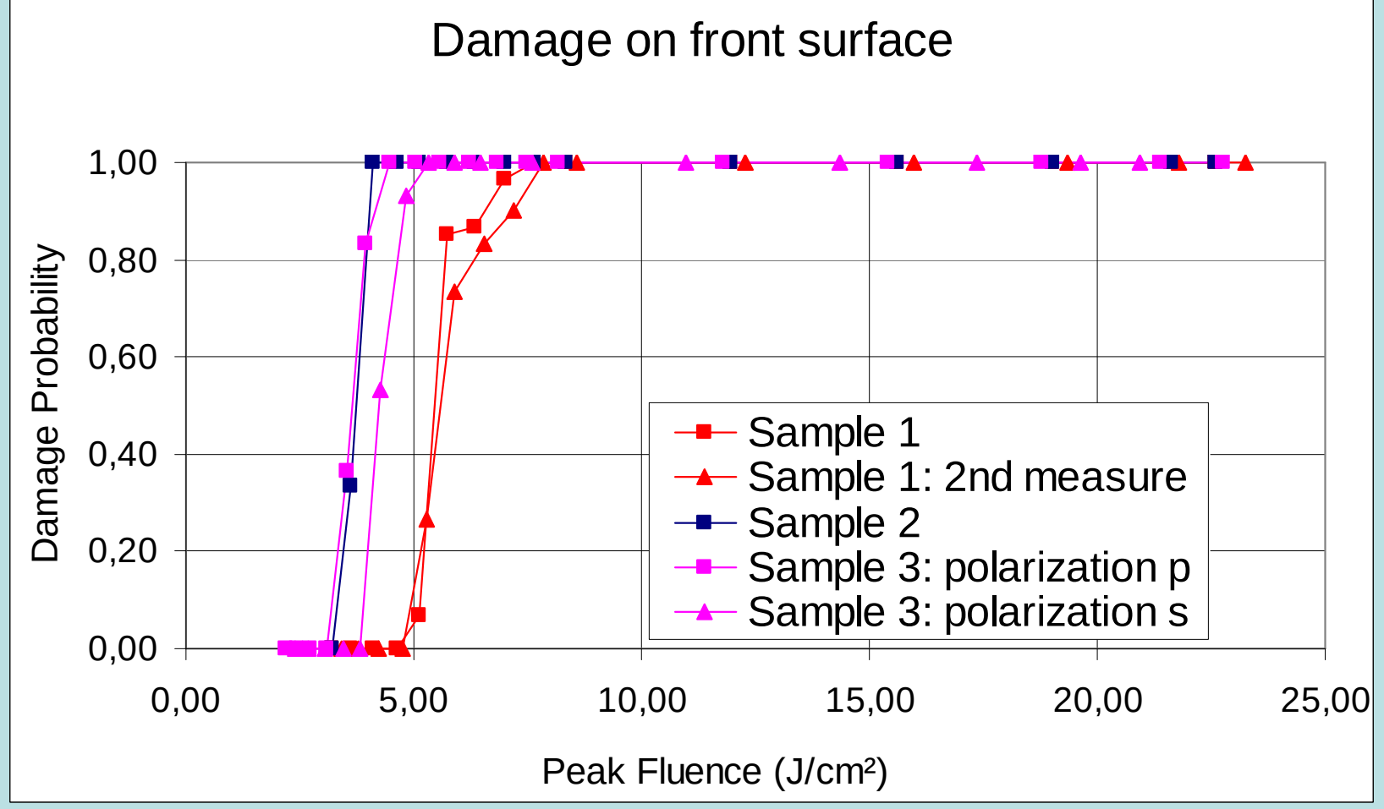
↳ possible filamentation in sapphire for fs tests but post-mortem analysis of samples shows that it does not occur (no damage under surface, similar morphology in ns and fs regimes)

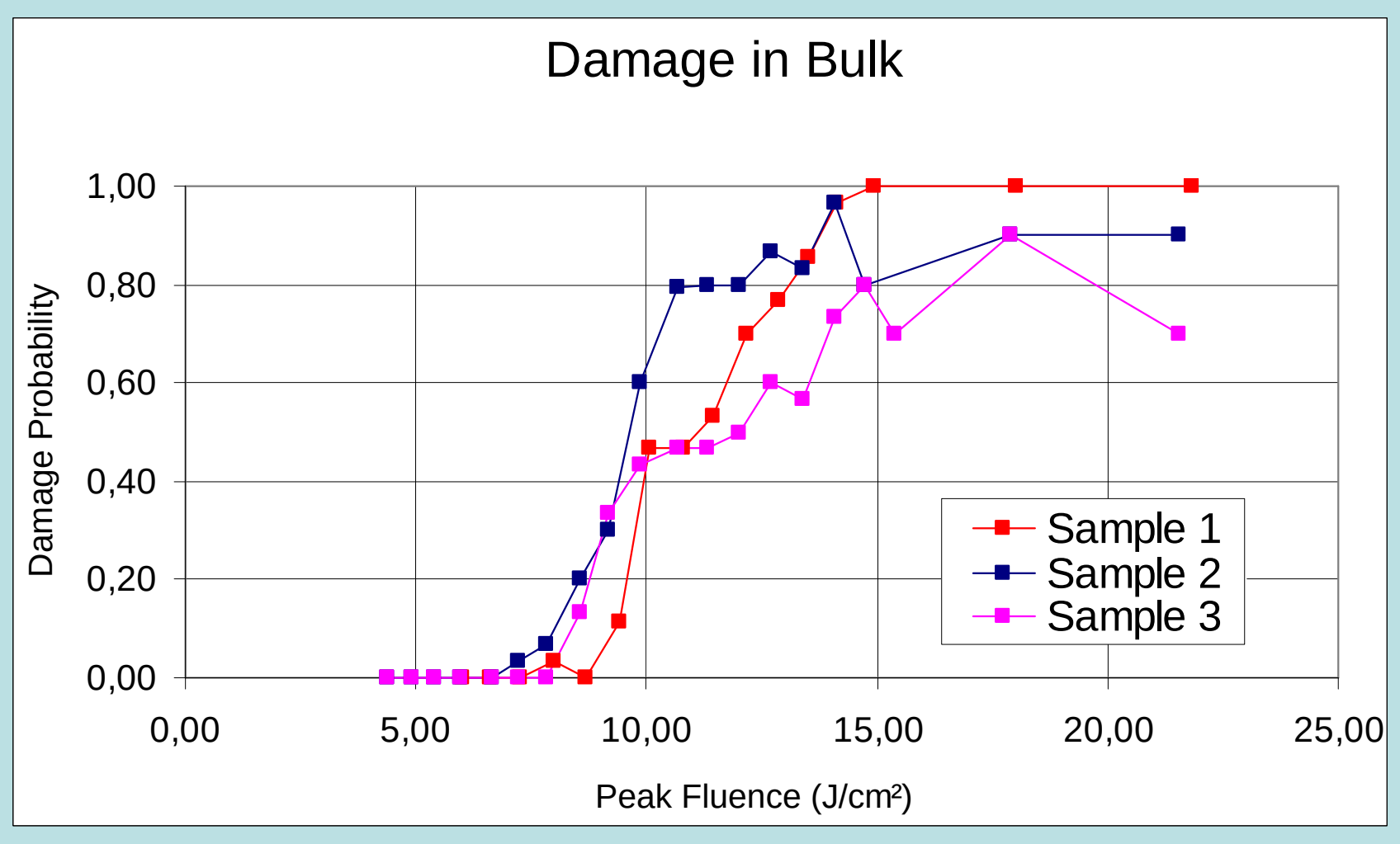
Results in Femtosecond regime

$2\omega_0$=21.6µm, z_r=350µm, λ=1025nm, test 1on1 (single shot)

➢ **Surface damage:**

- Good reproducibility of threshold measurement
- Better surface polishing improves threshold fluence value
- Doping level does not seem to play an important role
- Transition sharpness (between low and high threshold) $\Delta F/F_{50\%} < 0.5$
- Polarization: σ-polarized beam (E⊥c) ⇨ higher damage threshold than π-polarized beam (E//c)





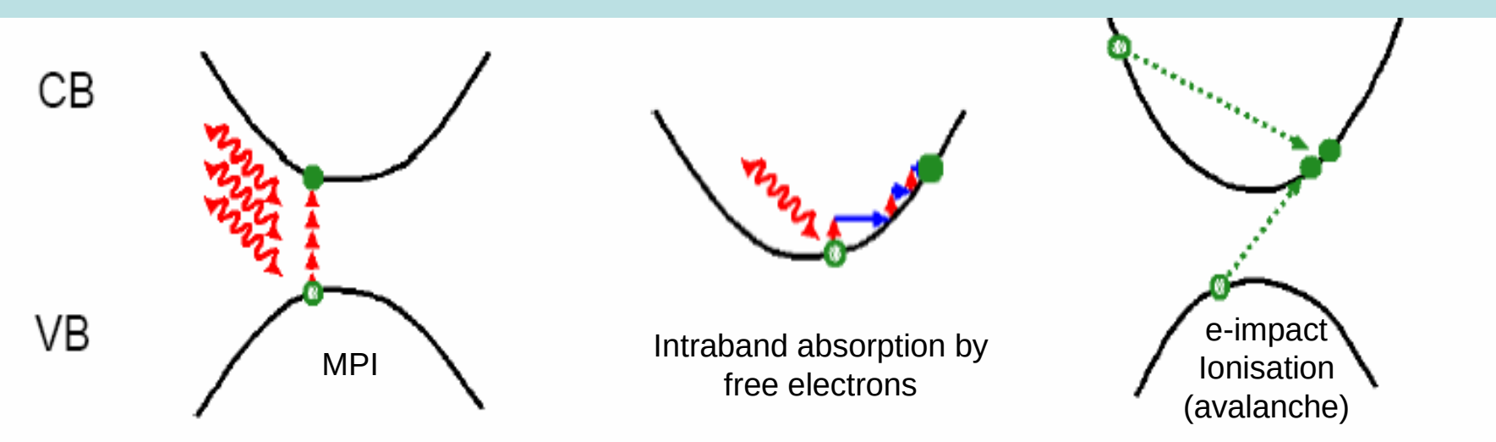
➢ **Bulk damage:**

- Bulk threshold appears to be higher than surface threshold: $E_{th,bulk}$~2x$E_{th,surf}$
- Spherical aberrations and focal volume have to be evaluated
- Doping level does not have strong effect on LIDT
- Small transition sharpness $\Delta F/F_{50\%}$: Damage detection problem? damage on defects?

Damage mechanisms in wide bandgap dielectrics

➢ **Femtosecond regime:** [3,4]

1. **NL photo-ionization : MPI or tunneling**
2. Avalanche ionization : exponential growth of e^- density



3. Energy transfer to material atoms
4. Damage of material (thermal and/or mechanical effects)

➢ **Nanosecond regime:** [1,3,5,6]

1. **Defect initiated mechanisms**
2. Energy transfer to host material
3. Damage of material (thermal and/or mechanical effects)

⇒ Probabilistic nature of ns damage

⇒ Damage is mainly defect-dependent in ns regime, and material-dependent in fs regime

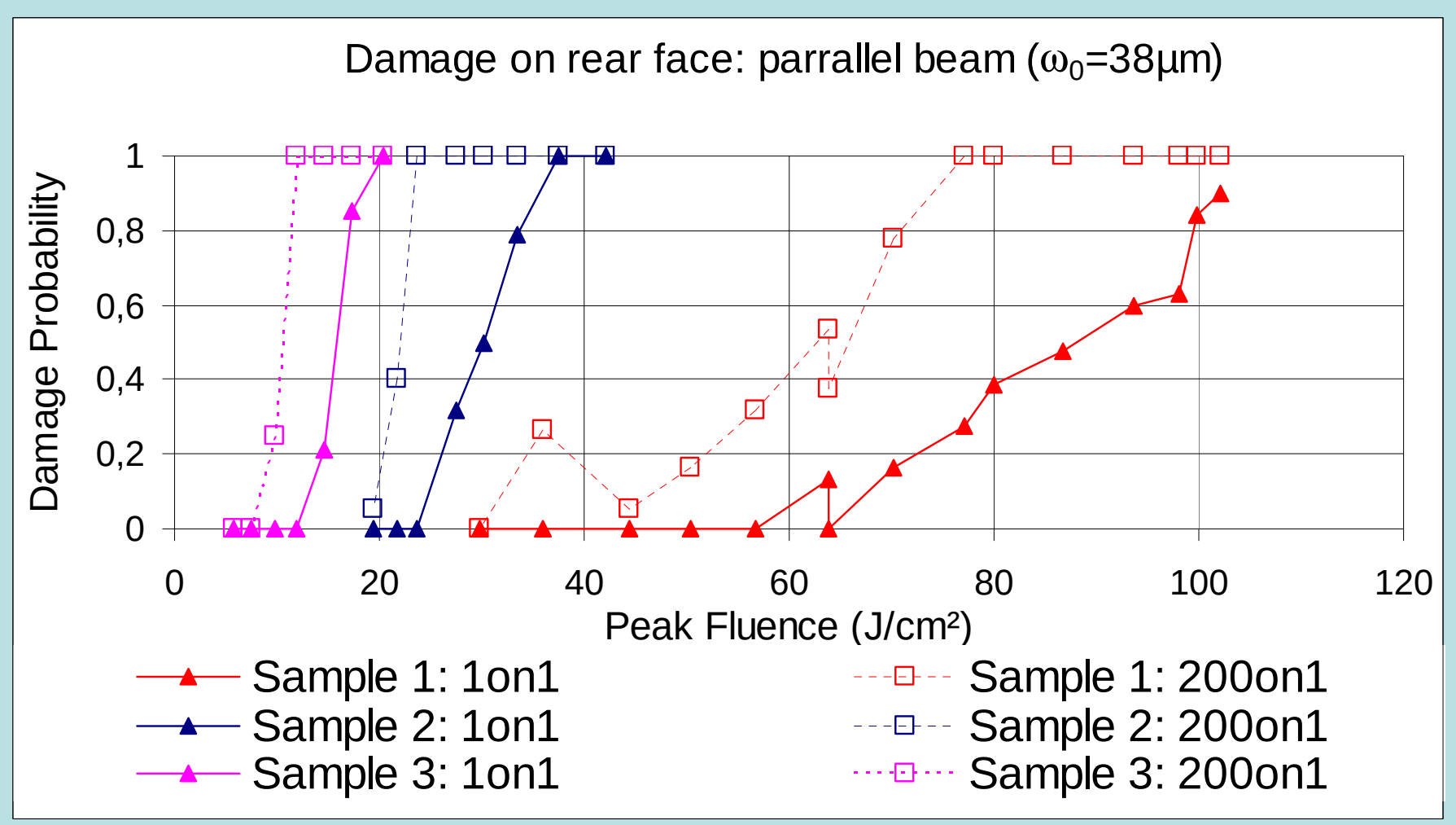
Results in Nanosecond regime

λ=532nm, test 1on1 (single shot) and 200on1 (fatigue @ 5Hz)

➢ **Irradiation by a low divergent beam:**

$2\omega_0$=76µm, z_r~8mm

- Damage occurs on the rear face due to interference close to rear surface [6]
- Importance of surface polishing
- Role of doping level and/or crystal orientation
- Fatigue effect $F_{th,200on1}$ ~ 0.5 to 0.8 $F_{th,1on1}$
- Transition sharpness: $\Delta F/F_{50\%} \geq 0.5$

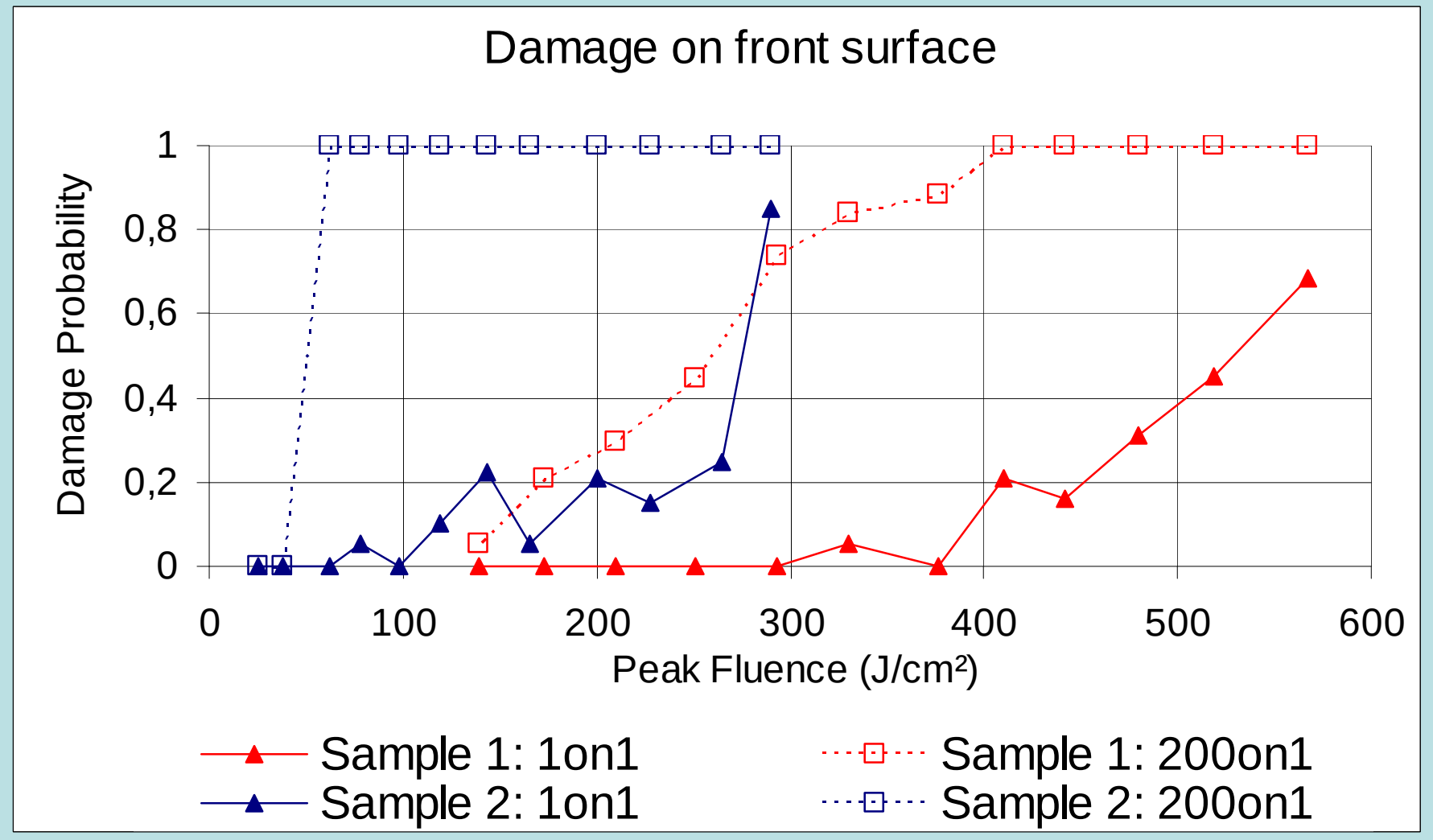


➢ **Irradiation by a tightly focused beam:**

$2\omega_0$=10.8µm, z_r=180µm

Front surface damage:

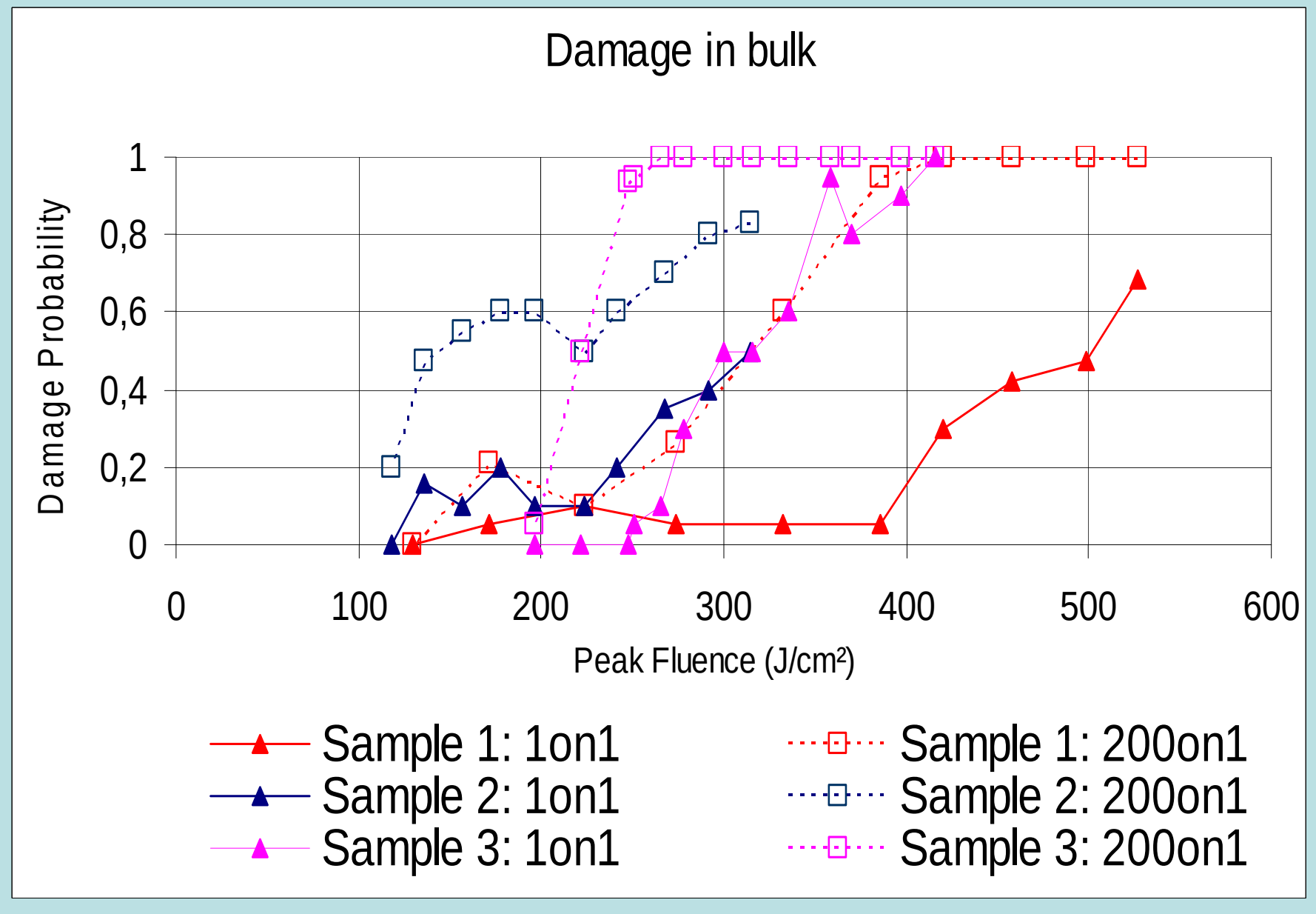
- Strong effect of surface polishing
- Strong fatigue effect : $F_{th,200on1}$ ~ 0.5 $F_{th,1on1}$
- Initiation on defects confirmed (see curves)



Bulk damage:

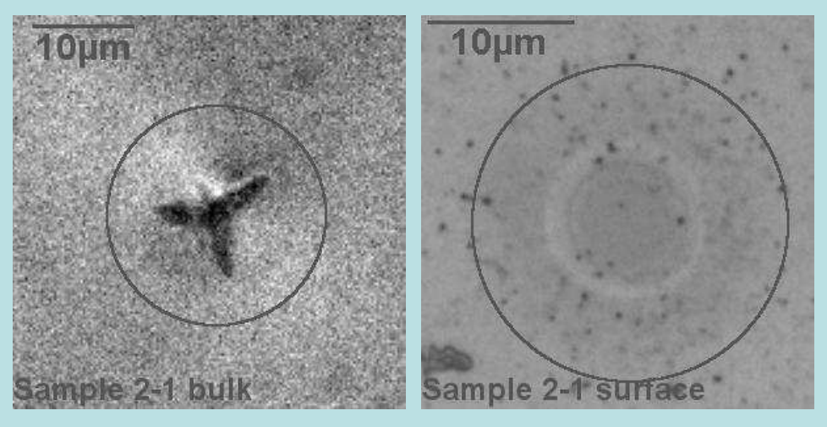
- Initiation on defects confirmed (see curves)
- Ti-doped Sapphire has a higher threshold than undoped sapphire
  ↳ Ti^{3+} doping is not a limiting factor and adds a new energy dissipation mechanism by emission processes (IR generation),
  ↳ Sharp transition: Ti^{3+} doping induced absorption seems to be the dominant mechanism leading to damage
- Fatigue more important for Ti-doped sapphire
- Undoped sapphire thresholds for bulk close to those for front face

NB : for Ti-doped sapphire, fluences are corrected from absorption losses



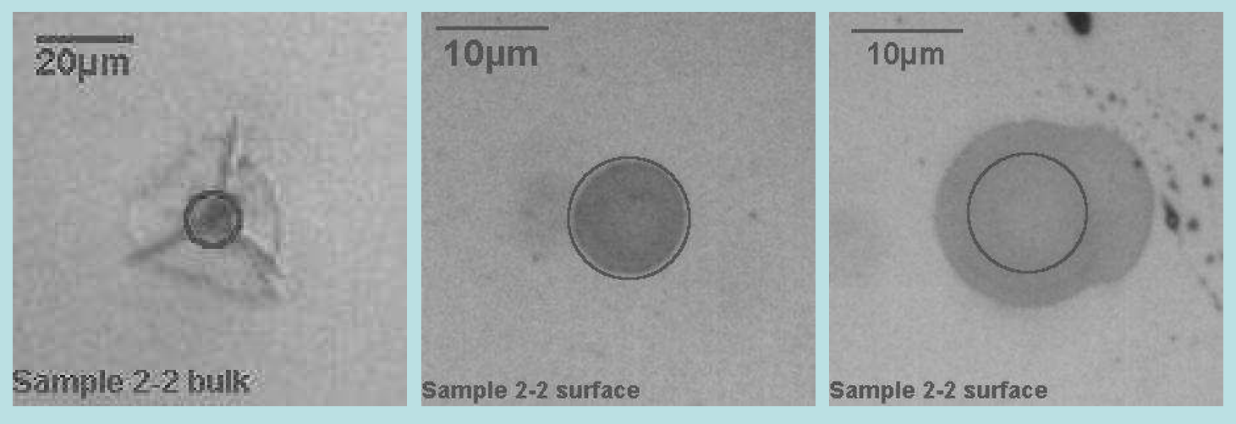
Morphology of damage :

Femtosecond, $2\omega_0$=21.6µm



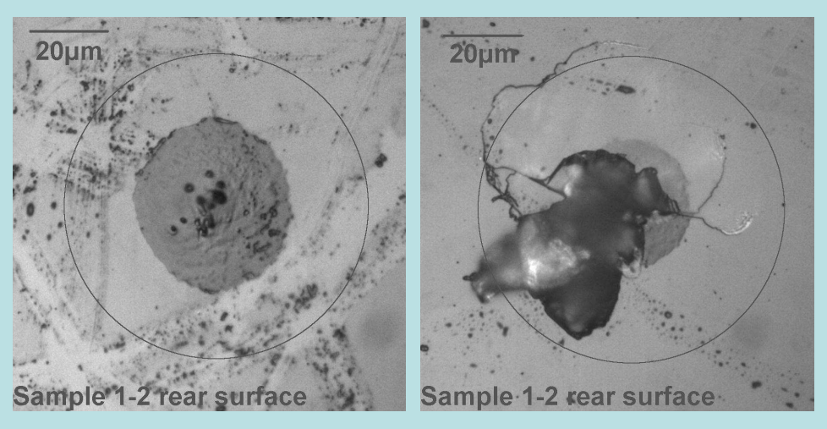
Bulk 3.2 x F_{th} — Front surface 3.7 x F_{th}

Nanosecond, $2\omega_0$=10.8µm



Bulk 1.25 x F_{th} — Front surface 1.25 x F_{th} 3.7 x F_{th}

Nanosecond, $2\omega_0$=76µm (low divergence)



Rear surface 1.4 x F_{th} 1.75 x F_{th}

➢ **Damage in bulk**: star-shaped damage along crystal cleavage planes (mechanical stress)

➢ **Tightly focused beam:**

- ns regime: damage size > beam size (circle) ⇨ High Heat Affected Zone (HAZ)
- fs regime: damage size < beam size (circle) ⇨ Low HAZ

↳ Damages seem to grow from beam center in both fs and ns regimes:
  - Sensitive to central peak fluence
  - No evidence of sensitivity to local surface defects has been observed

➢ **Low divergent beam:** damage occurs on rear face, but with different kinds of morphology: damages grow from local defects, constructive interference close to exit face [6]
⇨ spallation of material, …

Conclusions & References

	Sample	Front Surface Low Threshold (J/cm²) 1on1*(Non1)*	Front Surface High Threshold (J/cm²) 1on1*(Non1)*	Bulk Low Threshold (J/cm²) 1on1*(Non1)*	Bulk High Threshold (J/cm²) 1on1*(Non1)*	Rear Surface Low Threshold (J/cm²) 1on1*(Non1)*	Rear Surface High Threshold (J/cm²) 1on1*(Non1)*
450fs	1	4,62 & 4,74	7,64 & 7,85	7,26	14,92		
	2	3,23	4,11	6,64			
	3 (E//c)	3,11	4,49	7,85			
	3 (E⊥c)	3,82	5,33				
7ns	1	293 *(~130)*	~640 *(410,7)*	129 *(129,2)*	~550 *(420,6)*	56,8 *(29,7)*	~105 *(77,1)*
	2	62 *(38,3)*	~300 *(62,5)*	118 *(~100)*	~420 *(~370)*	23,7 *(~19)*	37,5 *(23,7)*
	3			248 *(~190)*	415 *(265,7)*	11,9 *(7,6)*	20,5 *(11,9)*

→ Importance of surface polishing for both fs and ns regimes
→ Ti^{3+} doping does not lower the damage threshold
→ Damage initiated by defects is confirmed in ns regime, even in fs regime (bulk)?
→ Fatigue phenomena observed in ns regime (no data available for fs regime)
→ Role of focusing geometry (importance of metrology)

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