# Irreversible material dynamics studied with time-resolved X-ray scattering

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Excitation of solid materials with ultrashort laser pulses represents an efficient way to generate states of high energy density. The relaxation of the optically excited state can lead to phase transitions on very short time scales and under conditions far from thermal equilibrium. In this contribution I will present some results from our recent work on the non-equilibrium structural response of strongly laser-excited materials, which demonstrate how the availability of ultrabright and ultrashort X-ray pulses has led to an improved understanding by providing a space- (to the atomic-level) and time-resolved insight into the underlying physical processes.

As one example I will present results on the formation of so-called **L**aser-**I**nduced **P**eriodic **S**urface **S**tructures (LIPSS), which are an almost omni-present phenomenon on laser-irradiated surfaces. LIPSS were first reported in 1965 [1] and have been observed on almost all types of materials and with any kind of laser (see [2] and references therein). However, due to the inherent multiscale nature of these irreversible processes the direct time-resolved observation of LIPSS formation has remained challenging.

In a proof-of-principle experiment at the VUV-FEL FLASH [3,4] we have demonstrated that time-resolved scattering with short-pulse XFELs can provide the required temporal and spatial resolution. More recently, we have extended this work with an experiment at the SCS-beamline of the European XFEL.

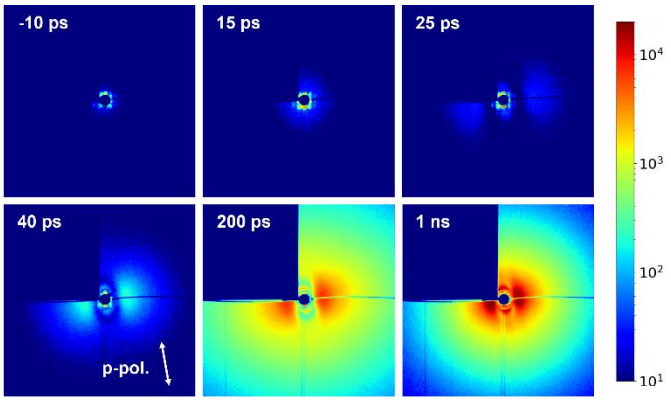


Fig. 1 shows in a false color representation a short sequence of transient scattering patterns measured on a 200 nm Ti film, which was excited by a p-polarized optical laser pulses (fluence 0.2 J/cm$^2$) and probed by a time-delayed, 1.5 keV X-ray pulse. They reveal a complex spatio-temporal evolution of periodic surface structures aligned along as well as perpendicular to the laser polarization (white arrow).

Other topics to be covered in this presentation (may) include laser-induced melting of metals, structural dynamics in supercooled liquids [5] and laser-ablation [6].

[1] M. Birnbaum, J. Appl. Phys. **36**, 3688 (1965); DOI 10.1063/1.1703071

[2] J. Bonse et al., IEEE J. Sel. Top. Quant. Elec. **23**, 9000615 (2017); DOI 10.1109/JSTQE.2016.2614183

[3] K. Sokolowski-Tinten et al., in: *Ultrafast Laser Nanostructuring* (eds. R. Stoian, J. Bonse), Springer Series in Optical Sciences **239**, 257 (2023); DOI 10.1007/978-3-031-14752-4_6

[4] J. Bonse et al., Laser & Photonics Reviews **18**, 2300912 (2024); DOI 10.1002/lpor.202300912

[5] P. Zalden et al., Science **364**, 1062 (2019); DOI: 10.1126/science.aaw1773

[6] Y. Sun et al., (under review 2024); DOI: 10.48550/arXiv.2407.10505