Strong nonlinear growth of energy coupling during laser irradiation of transparent dielectrics and its significance for laser induced damage

[Or how to deal with nonlinear phenomena with low laser intensities]

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Overview

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Laser damage in ICF class apertures

Pulse characteristics

Nanosecond timescale

$\lambda = 351$ nm

$F \simeq 20\ J/cm^2$; $I \simeq 10 GW/cm^2$

Optical components

Frequency converters : KDP and DKDP crystals

Grating or lens : fused silica SiO_2

Some problems...

Damage is observed

Need to understand the physical processes responsible for damage

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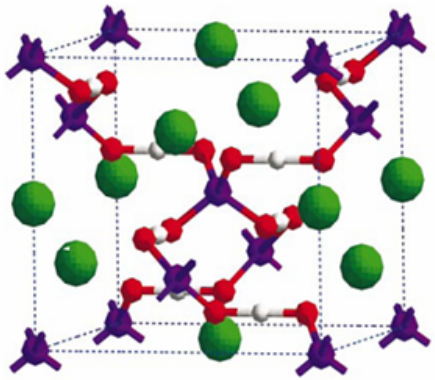
KDP structure



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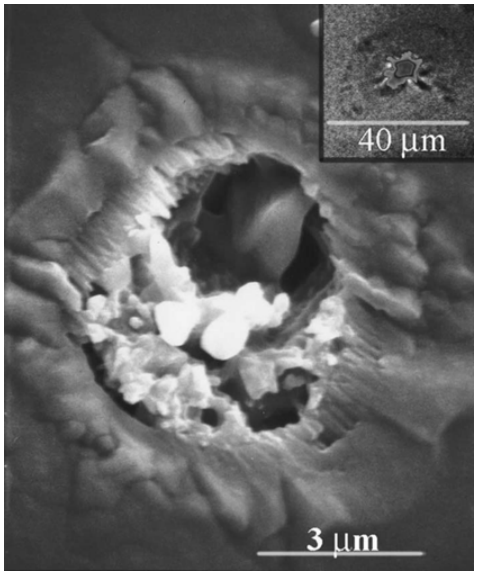
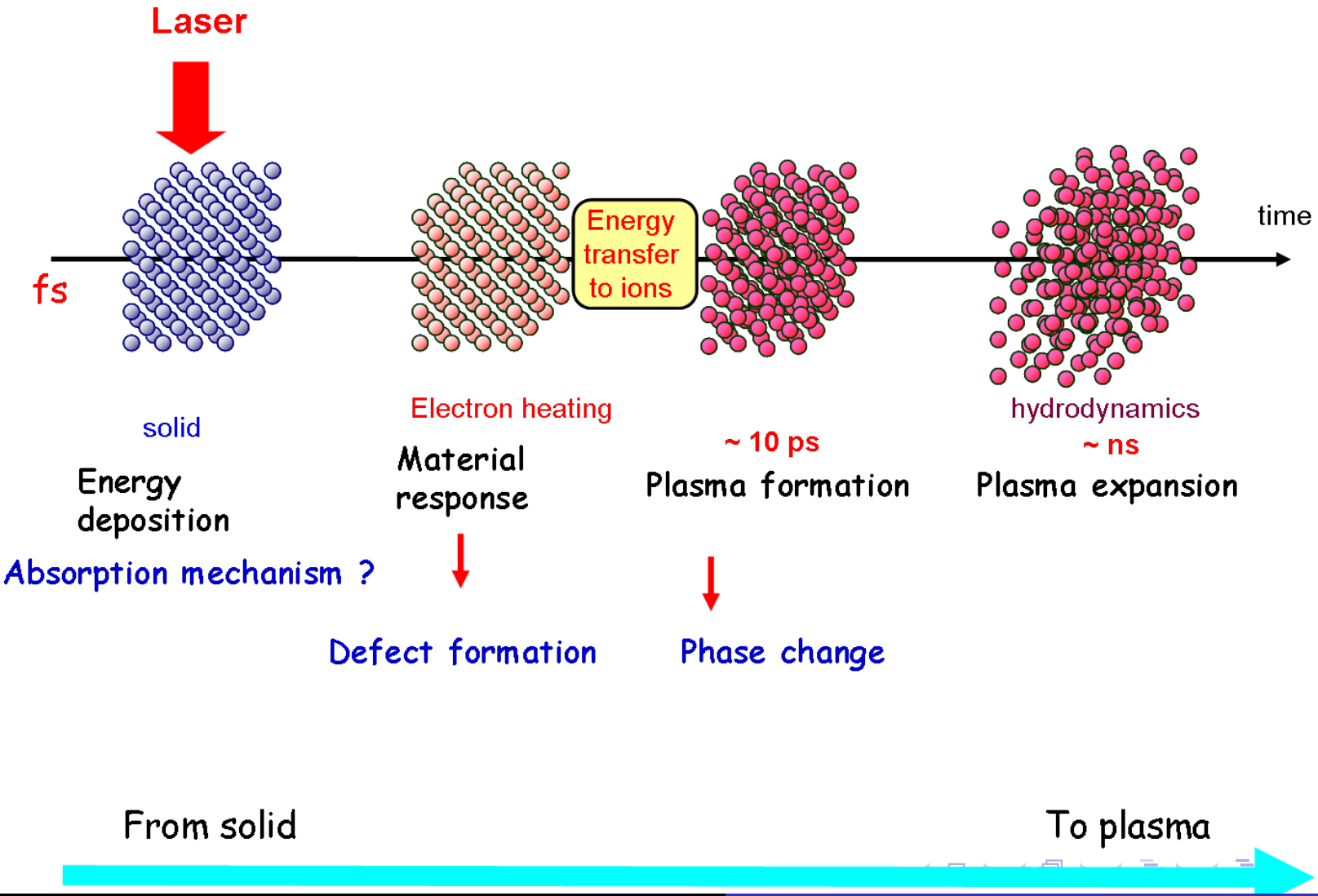
Standard damage in KDP crystals



Physics of laser damage



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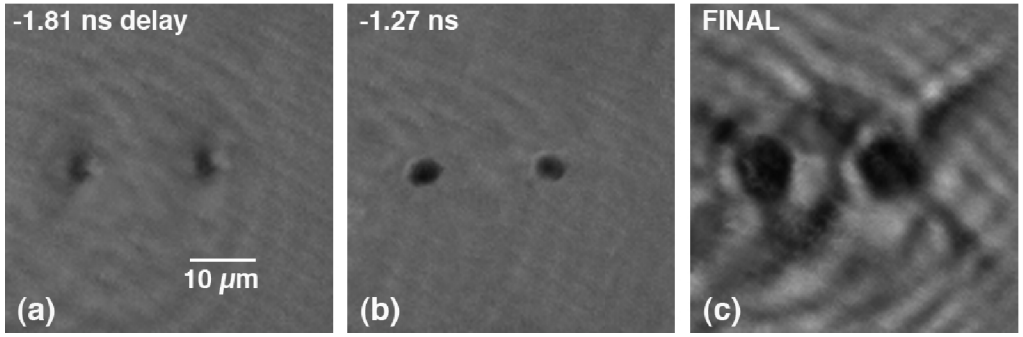
Time-resolved damage in KDP crystals

Transient images of 2 forming damage sites



Parallel and cross-polarized components

Conclusions

- $V_{AF2} \simeq 2km/s = 2\mu m/ns$
- Visualisation of damage precursors
- Initial step : build up of localized absorption + expansion via heating

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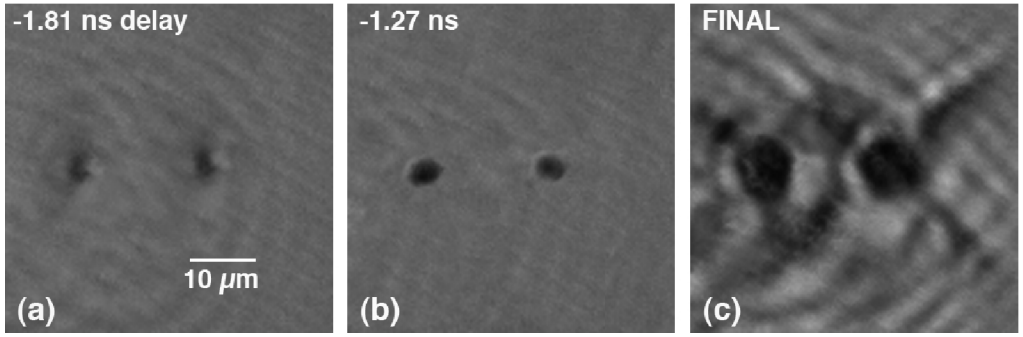

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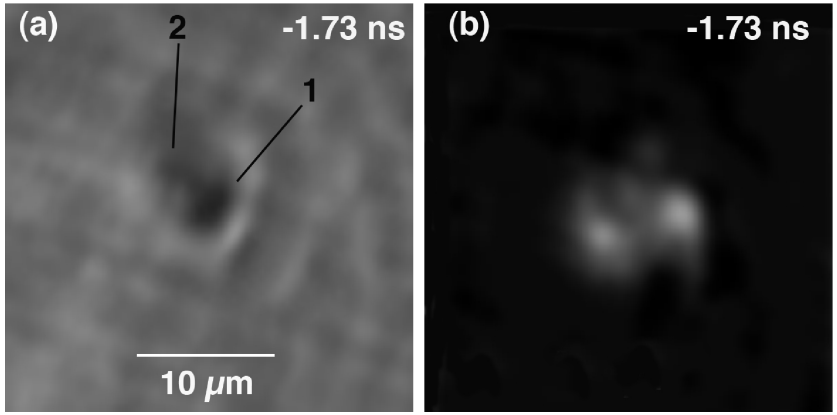

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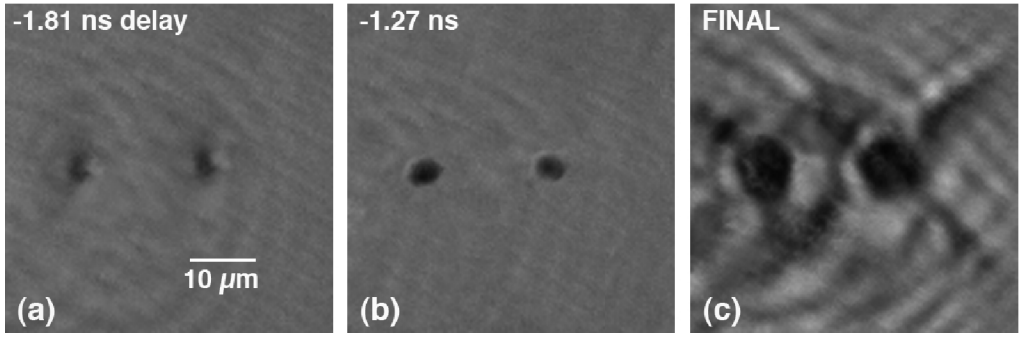

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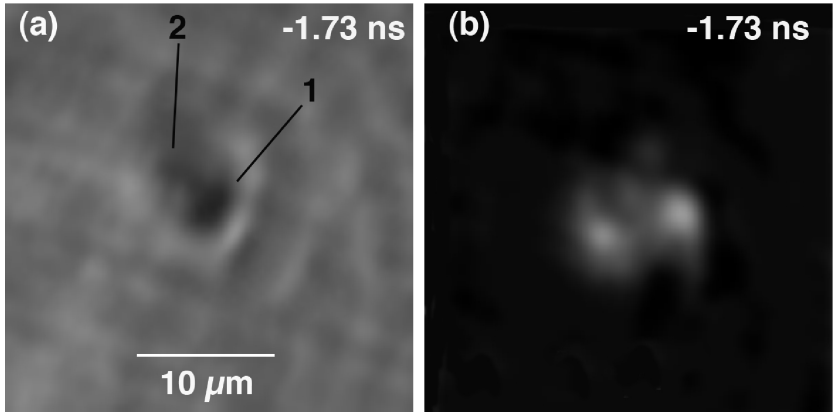

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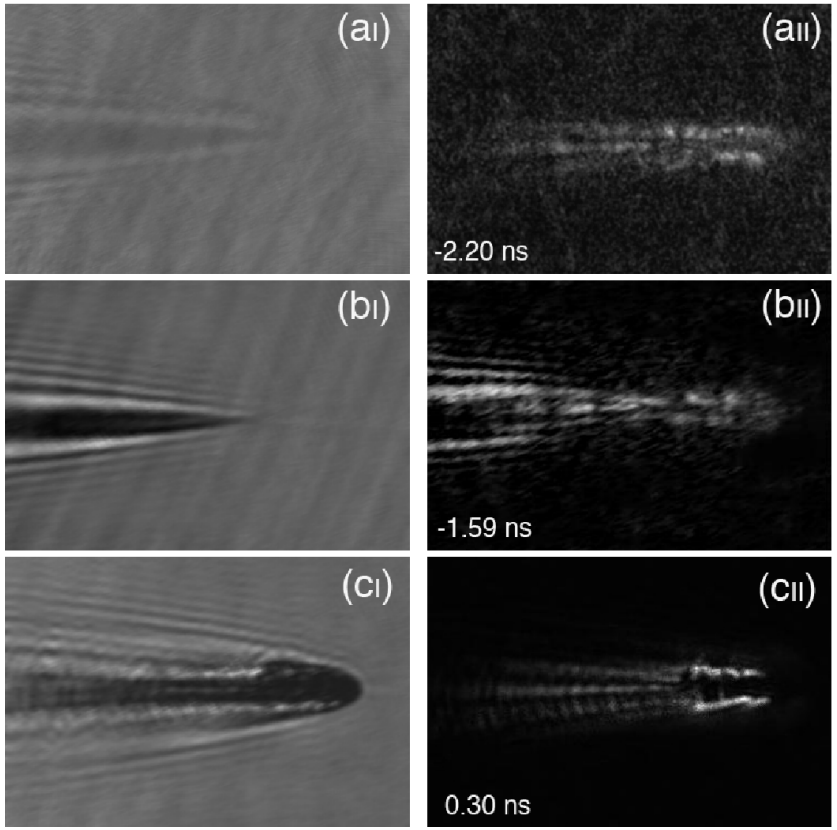

$$I \simeq 240\,GW/cm^2$$

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- Launching of a shock wave
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- $(c_s = 5.9km/s = 5.9\mu m/ns)$

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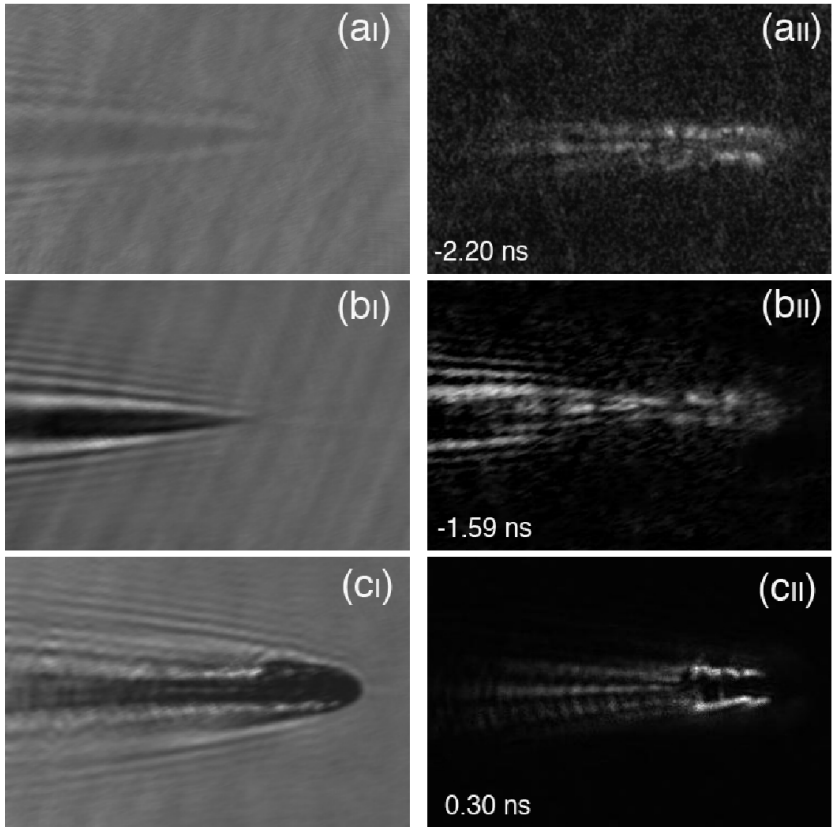

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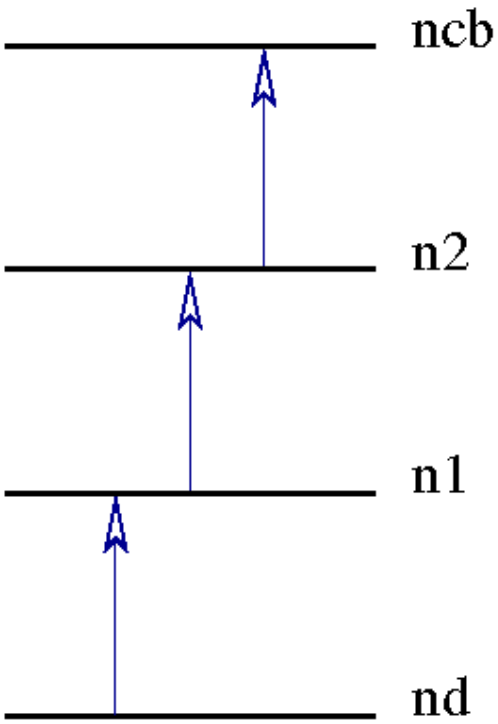
Electron dynamics

Sequential one-photon absorptions



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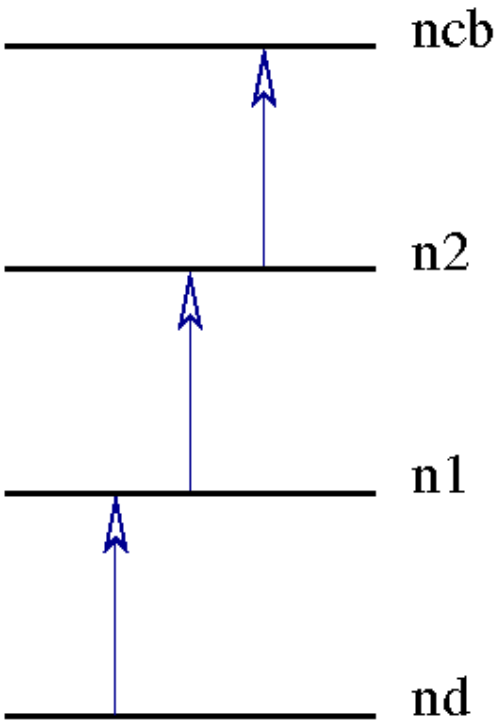

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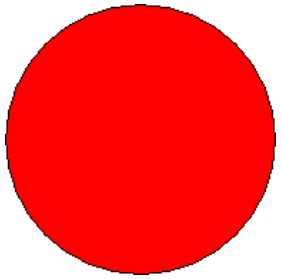
Heat diffusion may form new absorbing point defects



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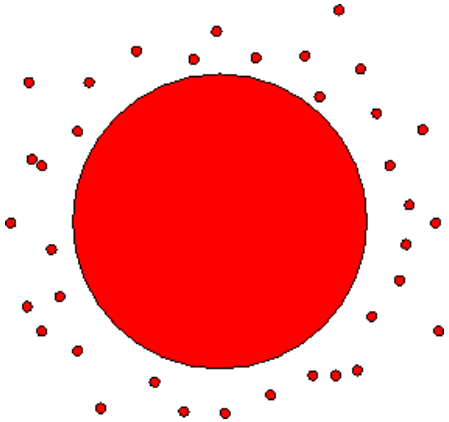

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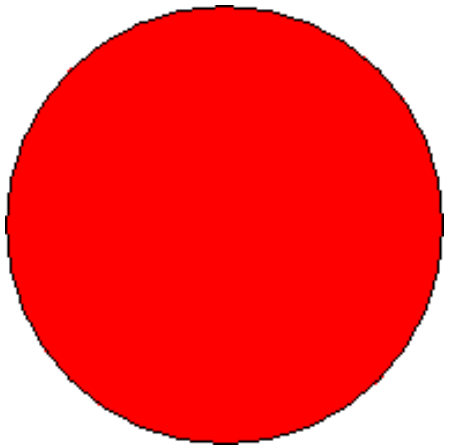

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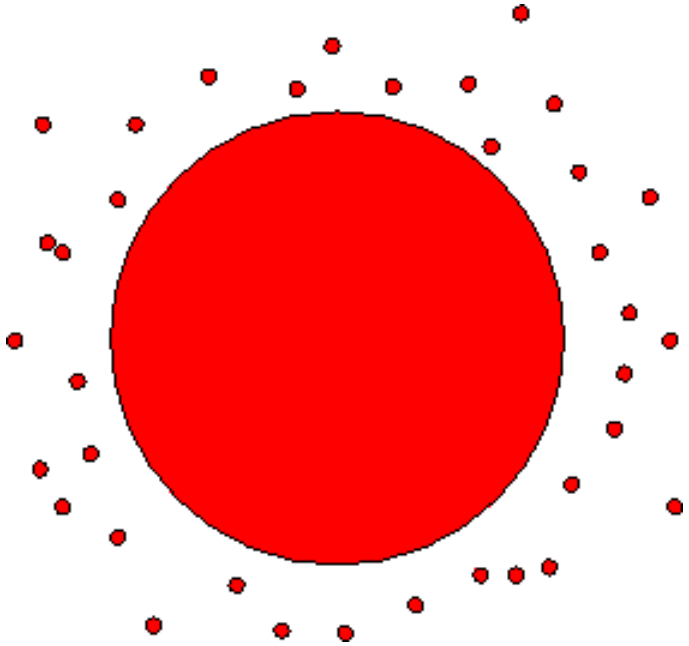

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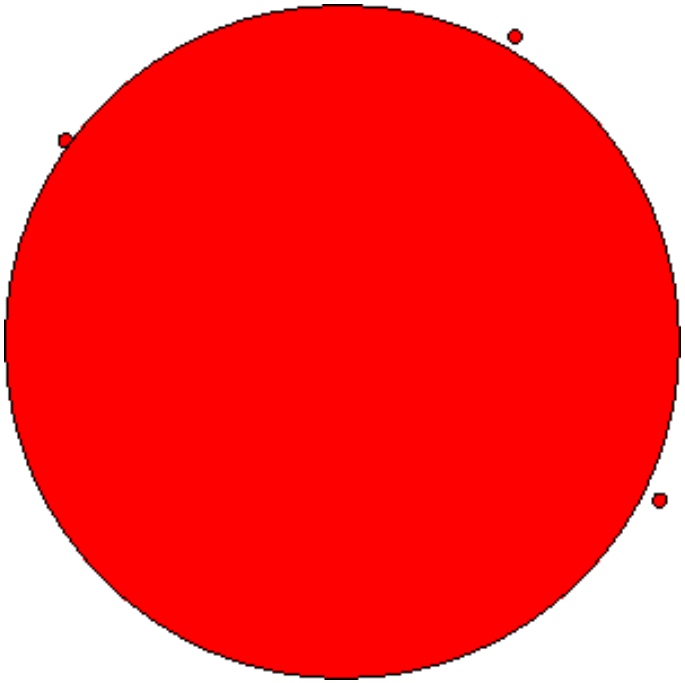

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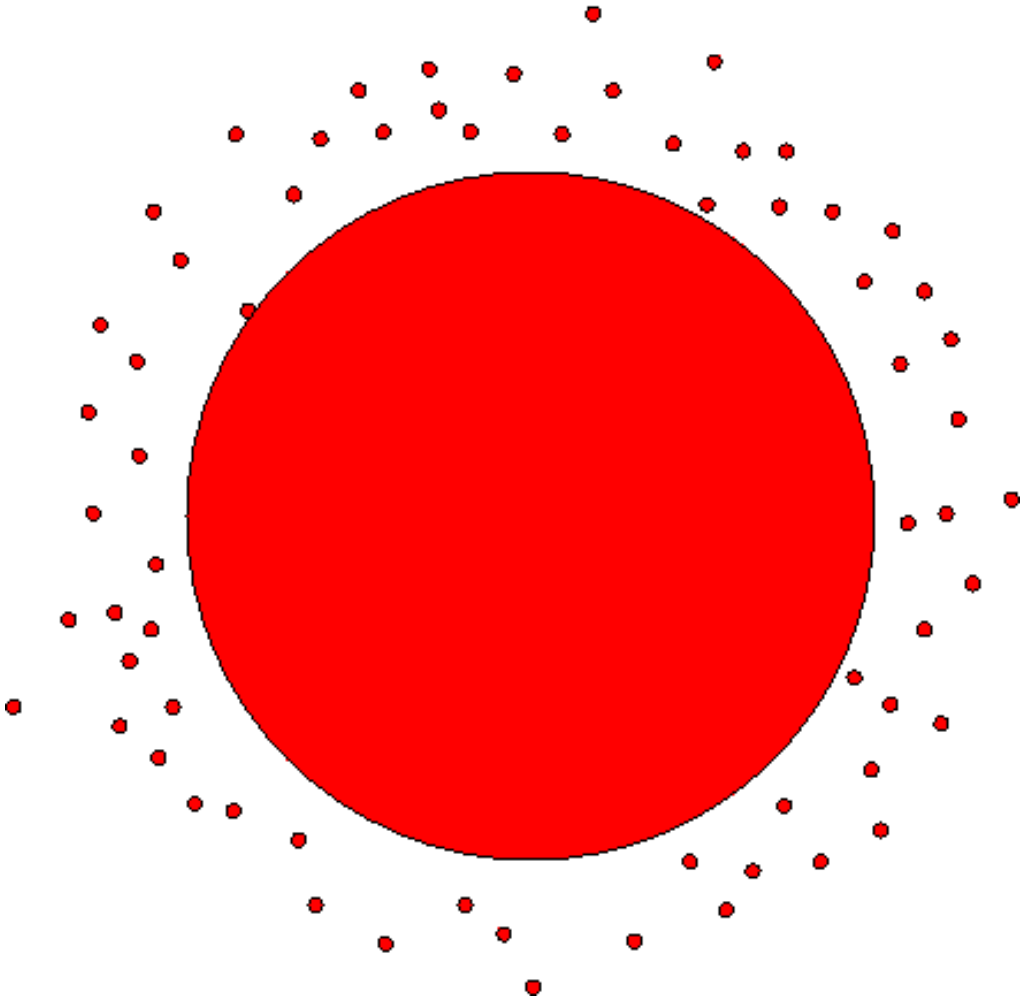

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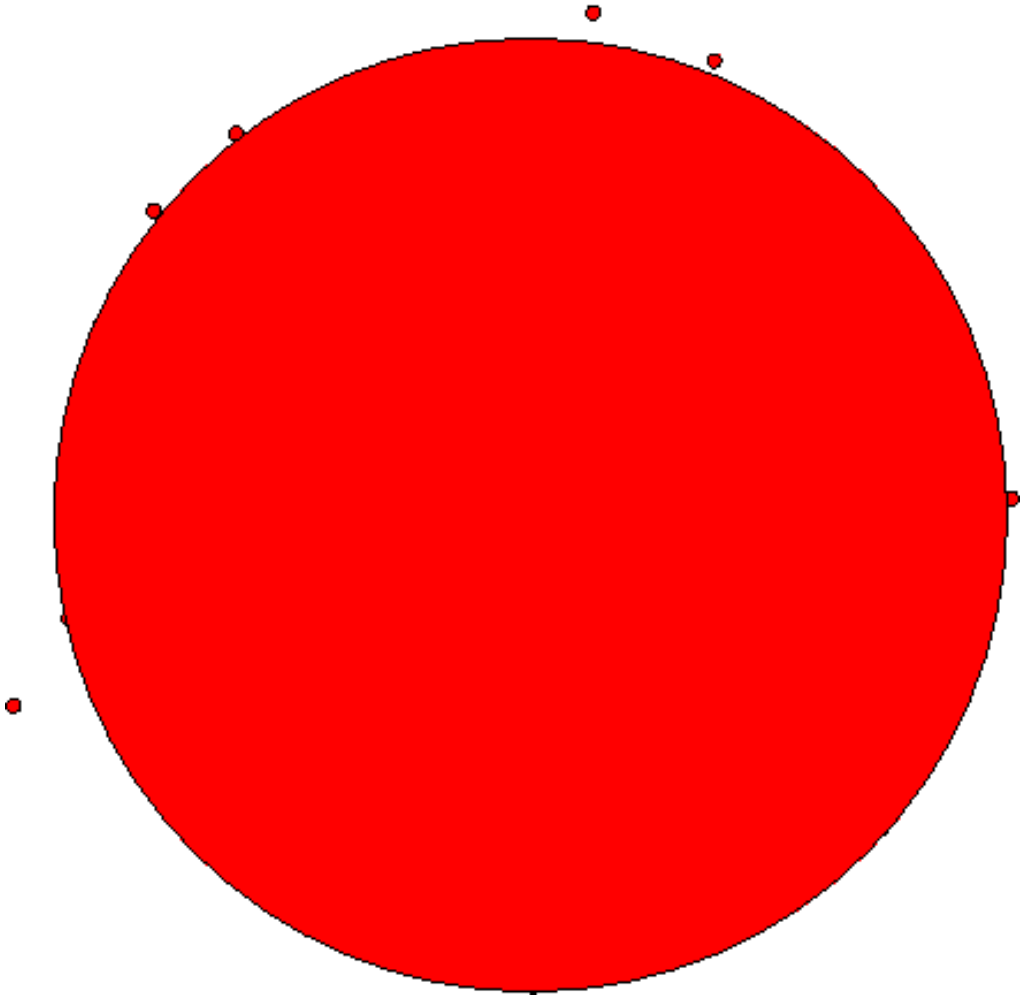
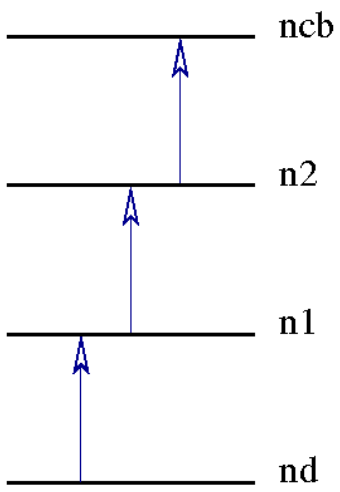


Energy transfer to the lattice, heat diffusion

Sequential one-photon absorptions



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a. G. Duchateau *et al*, J. Appl. Phys. **111**, 093106 (2012)

Energy transfer and diffusion

$$C\frac{\partial T}{\partial t} = \nabla(\kappa \nabla T) + (n_1 E_{01}/\tau_1 + n_2 E_{12}/\tau_2 + n_{cb} E_{23}/\tau_3 - E_a \frac{\partial N_d}{\partial t} + S_{iB} n_{cb})$$

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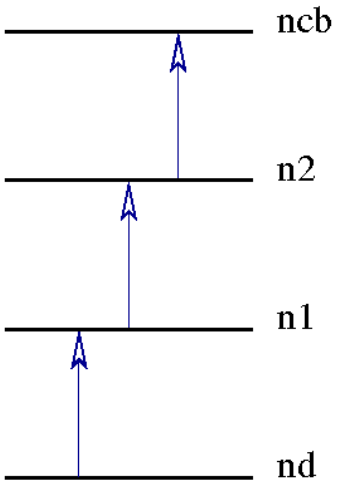

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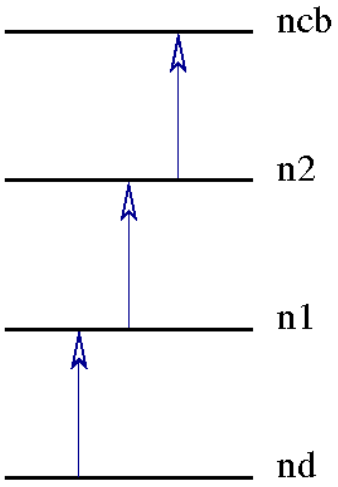

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Physical ingredients

Density of point defects

$$\begin{cases} N_d(r,t) = n_0 + K_0 \exp\left(-\frac{E_a}{kT(r,t)}\right) \text{ inside the precursor defect} \\ N_d(r,t) = K_0 \exp\left(-\frac{E_a}{kT(r,t)}\right) \text{ outside the precursor defect} \end{cases}$$

Inverse Bremstrahlung absorption

$$S_{iB} = \frac{e^2 \hbar \omega F_p}{8mc\varepsilon_0(\omega^2+\nu_c^2)}\nu_c$$

Thermal conductivity

$$\kappa(r,t) = \kappa_i + \kappa_e(r,t)$$

$$\frac{\kappa_e}{\sigma} = \frac{3}{2}\left(\frac{k_B}{e}\right)^2 T \rightarrow \kappa_e = \frac{3}{2}k_B^2 \frac{n_{cb} T \nu_c}{m(\omega^2+\nu_c^2)}$$

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Initial conditions

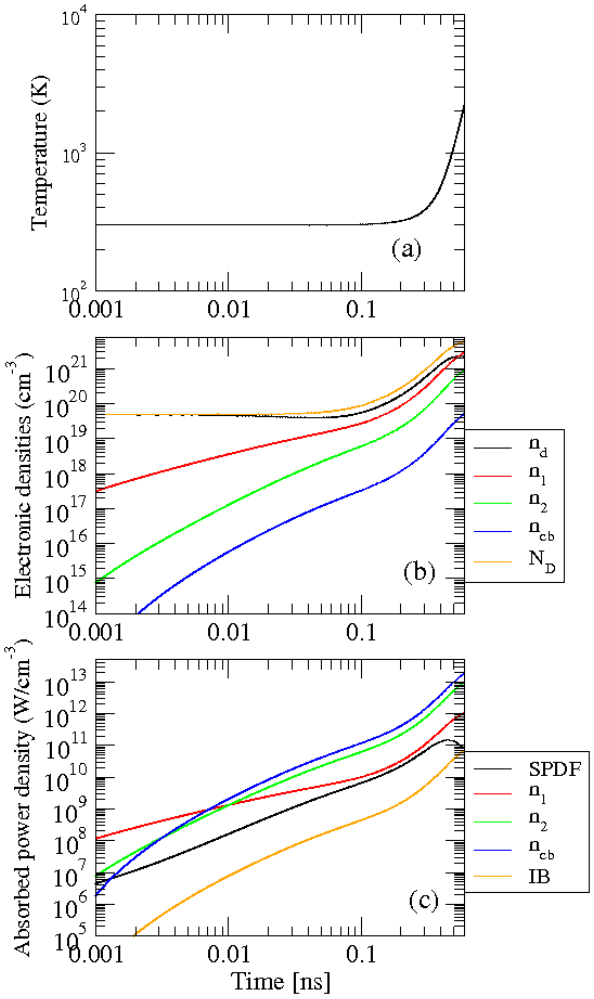
$$\text{Inside the precursor defect } (r \leq 100\ nm) : \begin{cases} n_{cb} = 0 \\ n_2 = 0 \\ n_1 = 0 \\ n_d = n_0 \\ T = T_0 \end{cases}$$

$$\text{Outside the precursor defect : } \begin{cases} n_{cb} = 0 \\ n_2 = 0 \\ n_1 = 0 \\ n_d = 0 \\ T = T_0 \end{cases}$$

Description of variables and parameters	Symbol	Value
Photon energy	$\hbar\omega$	$3.54\ eV$
Laser intensity	I	$3\ GW/cm^2$
one-photon absorption cross section	σ_1	$1.5 \times 10^{-18}\ cm^2$
one-photon absorption cross section	σ_1'	$7\sigma_1$
Recombination time	τ_1	$1\ ns$
Recombination time	τ_2	$50\ ps$
Recombination time	τ_3	$1\ ps$
Energy gap between ground state and level 1	E_{01}	2.3
Energy gap between level 1 and level 2	E_{12}	3.2
Energy gap between level 2 and CB	E_{23}	2.2
Collisional frequency	ν_c	$10^{15}\ s^{-1}$
Heat capacity	C	$2\ J/K/cm^3$
Thermal diffusivity of DKDP	D_i	$10^{-6}\ m^2/s$
Room temperature	T_0	$300\ K$
Initial point defect density	n_0	$5 \times 10^{19}\ cm^{-3}$
Maximum point defect density	K_0	$10^{22}\ cm^{-3}$
Energy of a hydrogen bond in KDP	E_a	$0.042\ eV$
Radius of the precursor defect	r_0	$100\ nm$

Overview

Evolution of physical quantities with time in $r = 0$



Conclusions

- Thermal explosion at $t \simeq 0.5ns$ ($T \simeq 500K$)
- $n_{cb} \simeq 10^{20} cm^{-3}$
- Non-radiative relaxation of conduction electrons is the main contributor to the T rise

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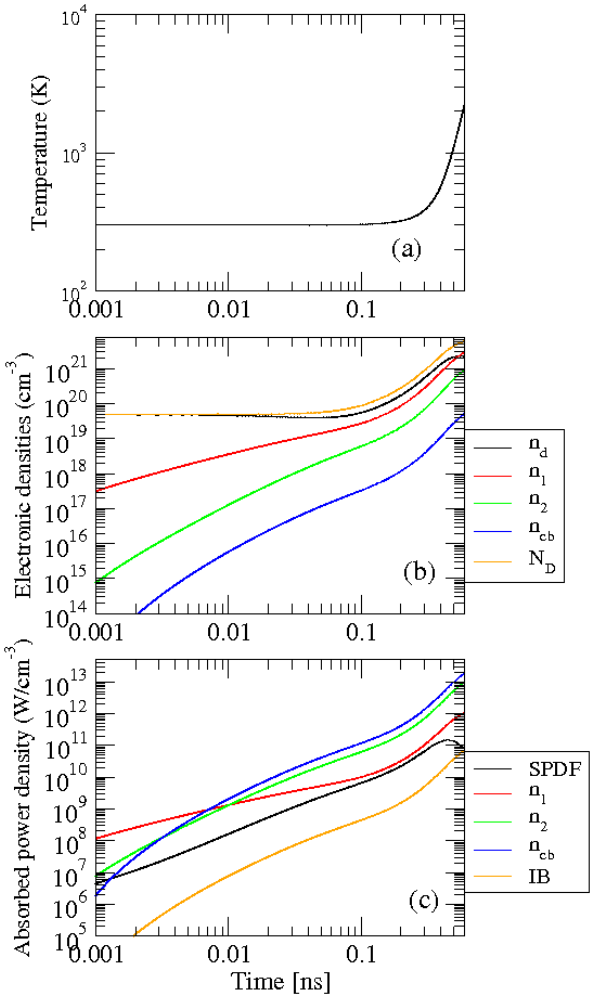

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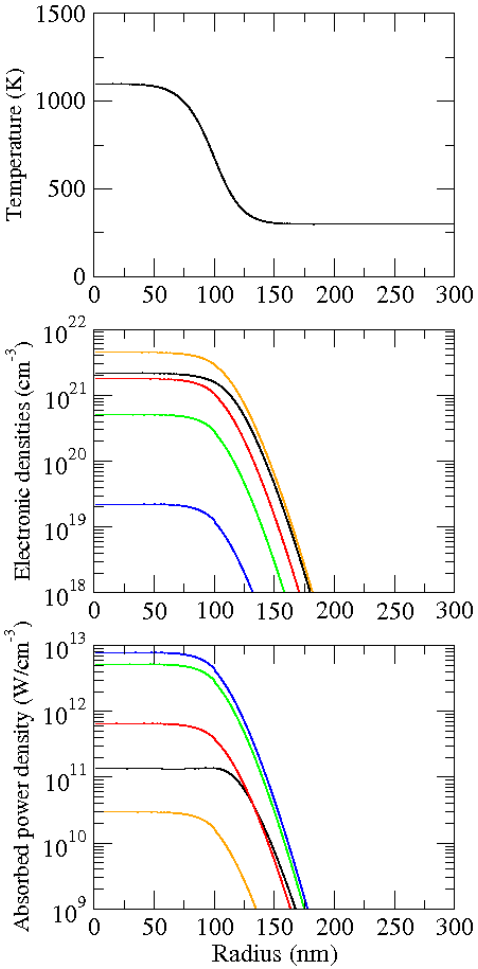

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Evolution of the size of the absorbing zone with time (outside the initial precursor volume)

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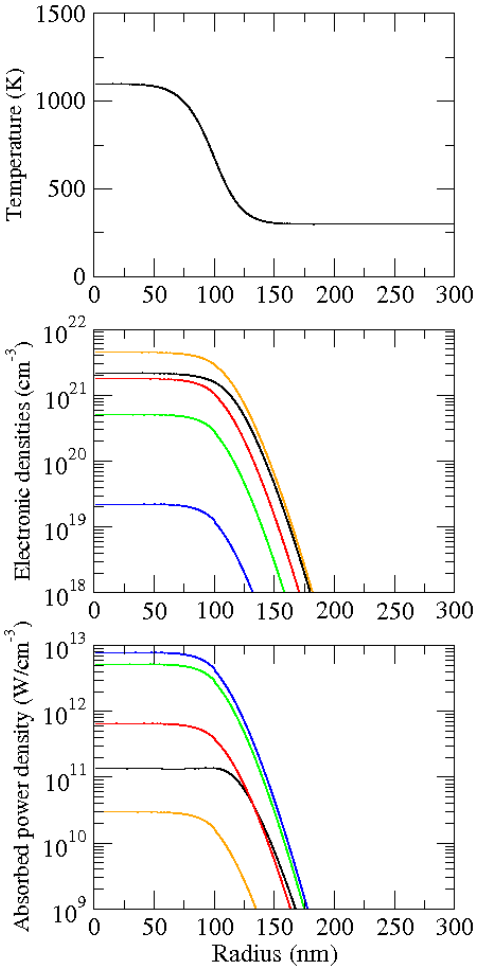

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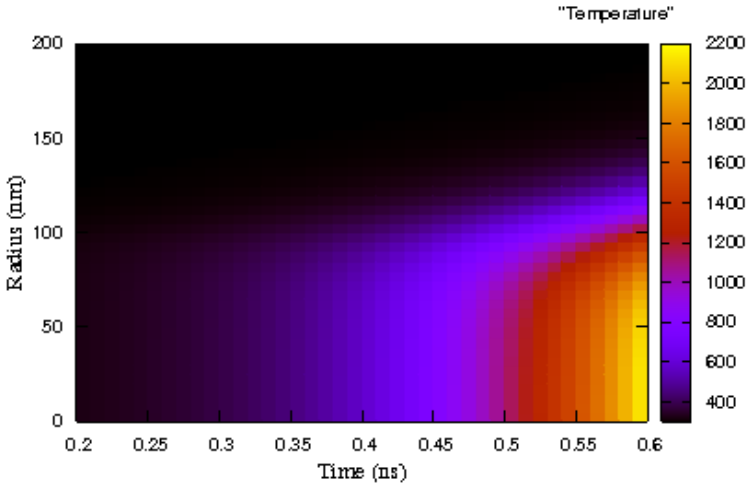

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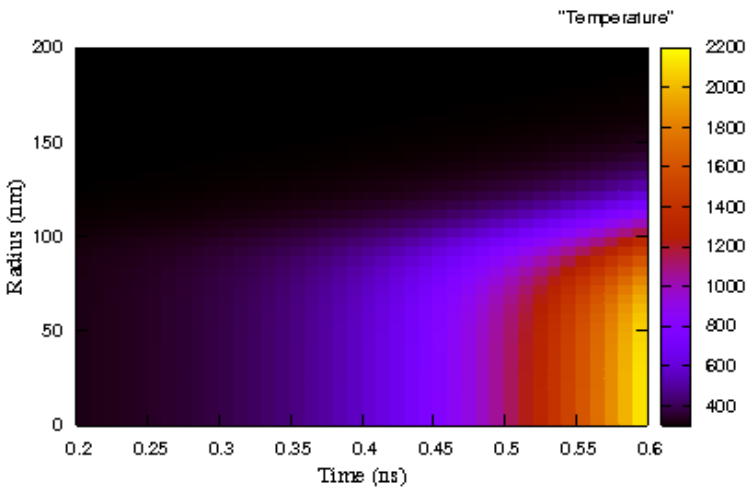

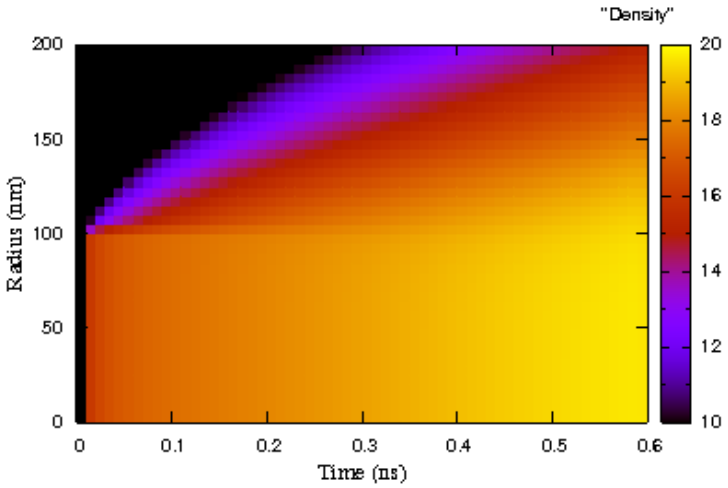

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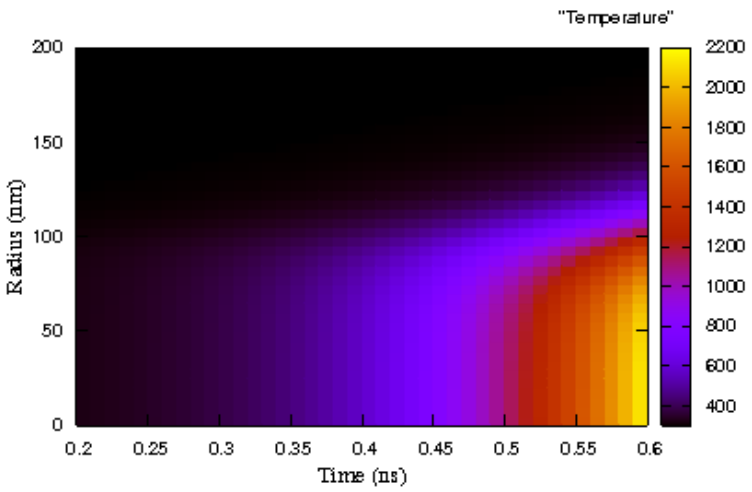

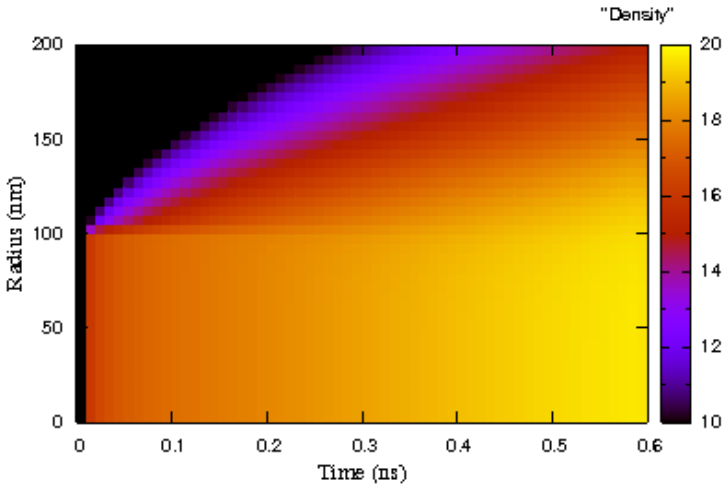

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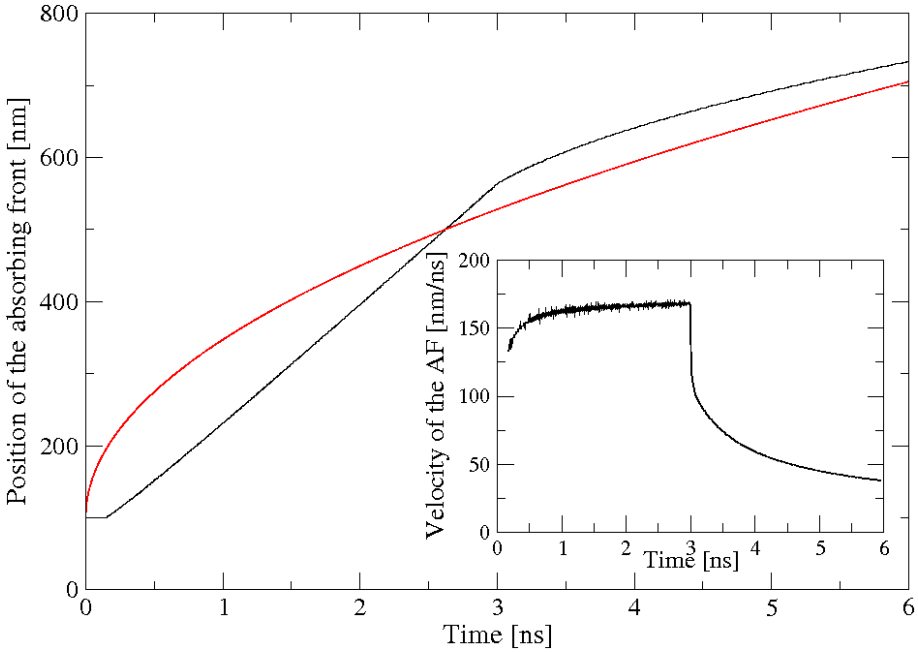
Speed of expansion almost constant

Evolution of the absorption front (AF) as a function of time

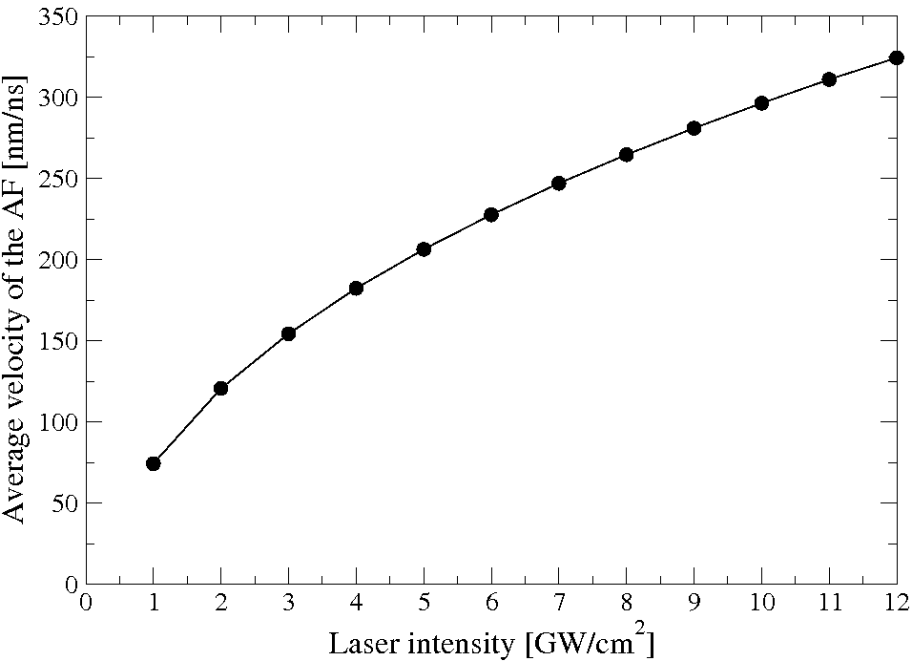


Definition of AF velocity

$$< v_{AF} >_t = \frac{1}{\tau} \int_0^\tau dt v_{AF}(t) = \frac{r_{AF}(\tau) - r_0}{\tau}$$

$$v_{AF} \simeq 170 nm/ns$$

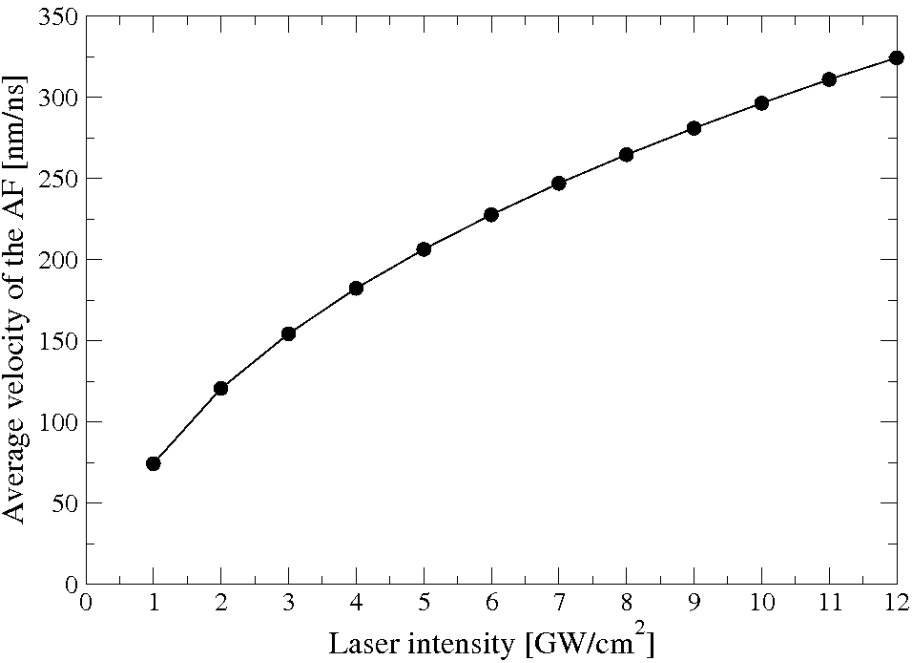
Evolution of the AF velocity as a function of intensity



Analytical estimates

$$\Gamma(T) = p\exp(-E_a/kT) = 1/\tau(T)$$
$$T = \alpha\frac{bI}{4\kappa}$$
$$\delta = C\sqrt{D\tau}$$
$$v_{AF} = \delta/\tau = C\sqrt{D\Gamma}$$
$$v_{AF} = C\sqrt{Dp}\exp\left(-\frac{\eta}{I}\right)$$
where $\eta = \frac{2\kappa E_a}{\alpha bk}$

Evolution of the AF velocity as a function of intensity



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Overview

Conclusions and outlooks

Main results

- Thermally-driven absorption modification based on point defect formation
- Damage results from a strong nonlinear energy coupling
- Time evolution of the absorbing area
- AF velocity is found to be one order of magnitude smaller than the speed of sound for standard laser illumination conditions
- Description of damage initiation in the ns regime

Acknowledgments

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