Ablation

The term ablation is generally used for material removal processes by photothermal (vibrational heating) or photochemical interactions (bond breaking).

In photothermal process, the absorbed laser energy gets converted into thermal energy in the material. The subsequent temperature rise at the surface may facilitate the material removal due to generation of thermal stresses. This is more pronounced in the inhomogeneous targets such as coated materials where the thermal stresses cause the explosive ablation of thin films.

When the incident laser energy is sufficiently large, the temperature at the surface exceeds the boiling point causing rapid vaporization. These processes of material removal by thermal stresses and surface vaporization are generally referred to as "thermal ablation".

In photoablation, the energy of the incident photon causes the direct bond breaking of the molecular chains in the organic materials resulting in material removal by molecular fragmentation without significant thermal damage.

This suggests that for the ablation process, the photon energy must be greater than the bond energy.

The ultraviolet radiation with wavelengths in the range 193–355 nm corresponds to the photon energies in the range 3.5–6.4eV. This range of photon energies exceeds the dissociation energies of many molecular bonds (C–N, C–O, C–C, etc.) resulting in efficient ablation with UV radiation.

It has been observed that ablation also takes place when the photon energy is less than dissociation energy of molecular bond.

This is the case for far ultraviolet radiation with longer wavelengths (and hence correspondingly smaller photon energies).

Such an observation is due to multiphoton mechanism for laser absorption.

In multiphoton mechanism, even though the energy associated with each photon is less than the dissociation energy of bond, the bond breaking is achieved by simultaneous absorption of two photons.

The laser material interaction during ablation is complex and involves interplay between the photothermal (vibrational heating) and photochemical (bond breaking) processes. One of the important considerations during the laser tissue interaction studies is the thermal relaxation time (τ).

Thermal relaxation time is related with the dissipation of heat during laser pulse irradiation and is expressed as;

$$\tau = \frac{d^2}{4K}$$

Where; d is absorption depth and K is the thermal diffusivity.

For longer pulses (with pulse time longer than thermal relaxation time), the absorbed energy will be dissipated in the surrounding material by thermal processes.

To facilitate the photoablation of material with minimum thermal damage, the pulse time must be shorter than that of thermal relaxation.
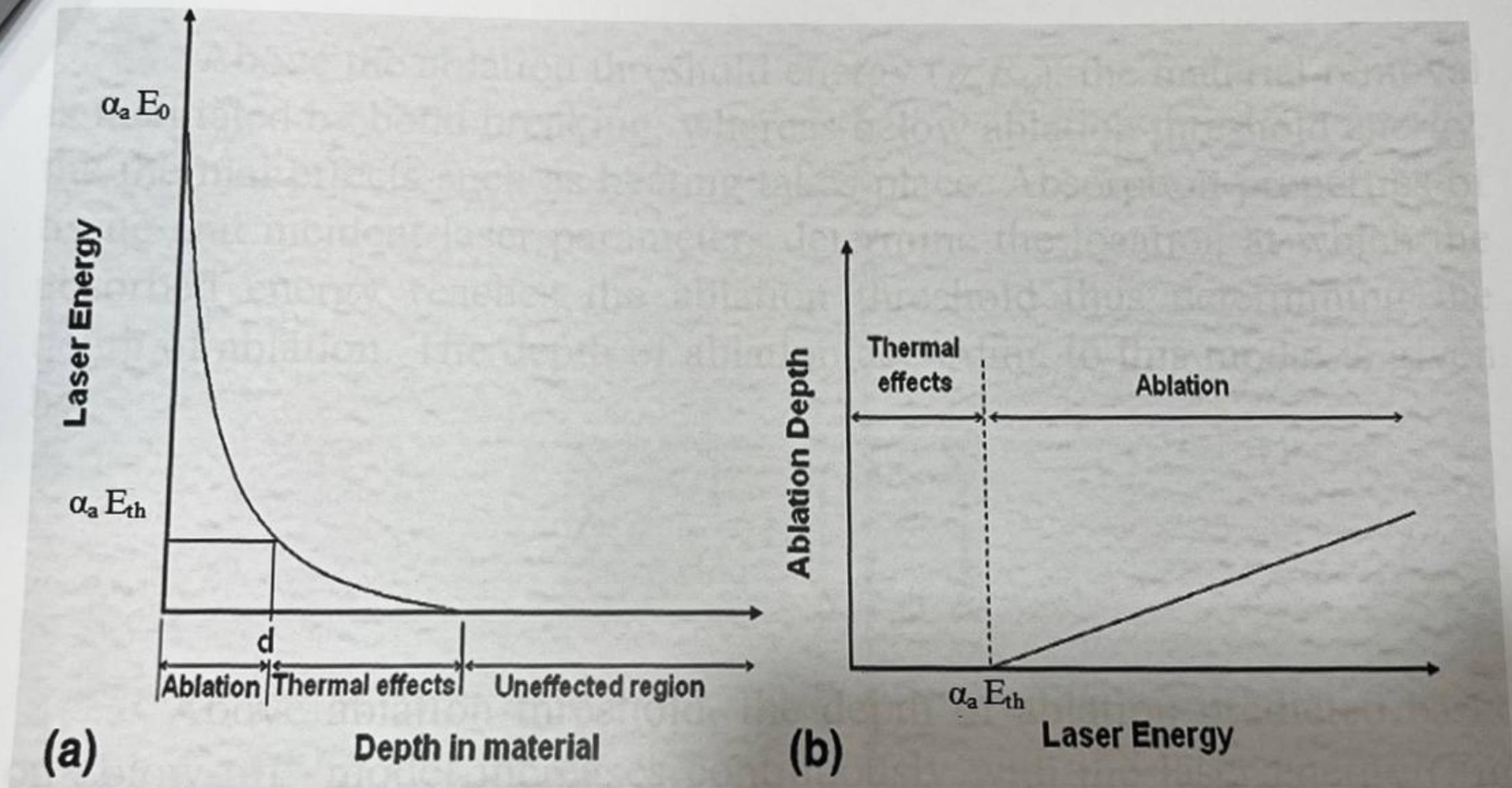
For such short pulses (pulse times in the range of microseconds), the laser energy is confined to a very thin depth with minimum thermal dissipation.

Thus, efficient ablation of the material during laser material interactions requires the laser operating at shorter wavelengths with microsecond pulses.

The ablation process is generally explained on the basis of "blow-off" model which assumes that ablation process takes place when the laser energy exceeds the characteristic threshold laser energy.

Ablation threshold represents the minimum energy required to remove the material by ablation.

Figure 14 presents the schematic distribution of absorbed energy in the material irradiated with incident laser energy E_0.

Figure 14: Blow-off model of laser ablation: (a) distribution of absorbed laser intensity in the depth of material and (b) variation of depth of ablation with laser energy.

Above the ablation threshold energy ($\alpha_a E_{th}$), the material removal is facilitated by bond breaking; whereas below ablation threshold energy, the thermal effects such as heating takes place. Absorption properties of tissue and incident laser parameters determine the location at which the absorbed energy reaches the ablation threshold thus determining the depth of ablation. The depth of ablation according to this model is given by:

$$\delta = \frac{1}{\alpha_a} \ln\left(\frac{E_0}{E_{th}}\right)$$

Above ablation threshold, the depth of ablation predicted based on "blow-off" model increases continuously with the laser energy (Fig. 14b). However, actual ablation depths depends on a number of other effects such as plasma shielding and radiation-induced changes in the material absorption coefficient which tend to deviate the actual ablation depth from that predicted by simple "blow-off" model.

The ablation rates are primarily determined by the;
laser fluence, the pulse duration, the number of pulses, and the pulse repetition rates (PRRs).

Figure 15 presents the influence of some of these parameters on the laser ablation of polymethylmethacrylate (PMMA) using krypton fluoride laser KrF (wavelength: 248 nm) and pulse duration of 30 ns.

As indicated in the Figure, there exists a threshold fluence below which no ablation is observed. Once the laser energy exceeds the ablation threshold, the ablation rates increase with laser fluence. In addition, for the constant laser fluence, the ablation rate increases with increasing number of pulses before eventual saturation.

Higher pulse repetition rates generally results in higher ablation rates. The ablation of material results in the formation of well-defined craters on the surface
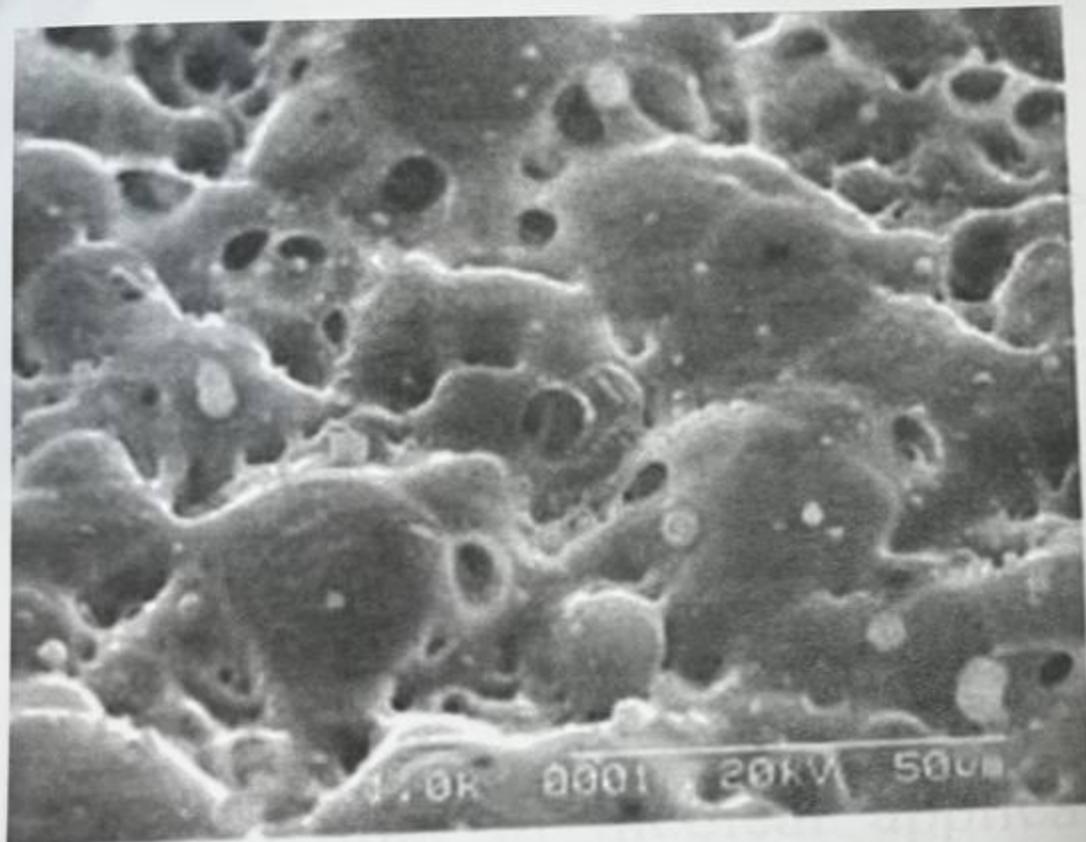
(a)

(b)

Figure 15: Morphology of the craters in PMMA ablated by 100 laser pulses with a fluence of 0.7 J/cm² and pulse repetition rate of **(a)** 2 Hz and **(b)** 10 Hz.

Pulsed laser ablation is extensively used in materials processing and medical applications.

In materials processing, it can be used for micromachining, marking, grooving, cutting, drilling, and patterning of wide range of materials.

While, in medical applications, it can be used for precision ablation of tissues such as human corneal tissues.
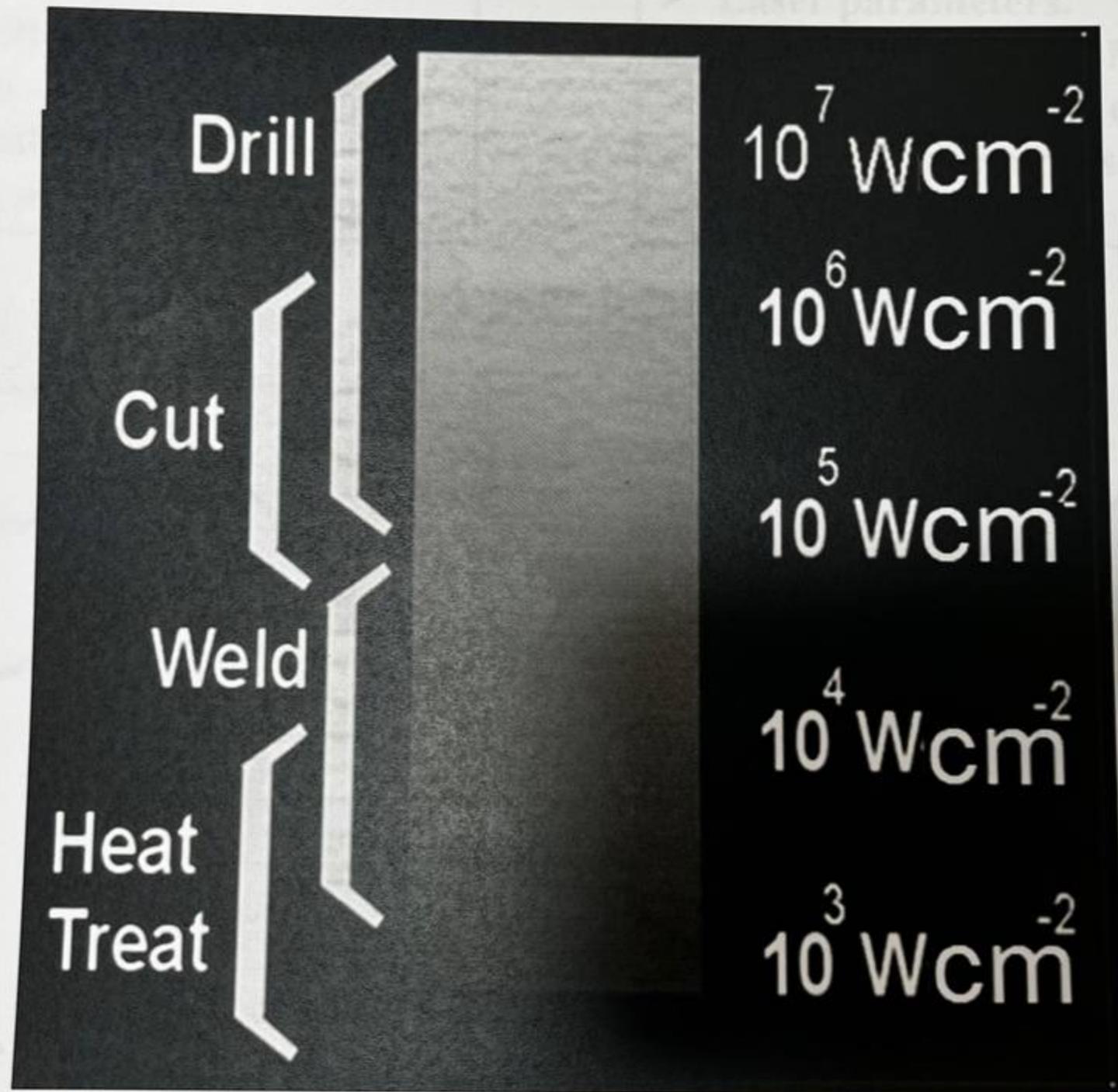
Figure 16: Laser power density regimes

- Light absorption.
- Temperature rise.
- Melting.
- Vaporization.
- Cooling and solidification.

- Laser parameters.
- Optical properties of materials
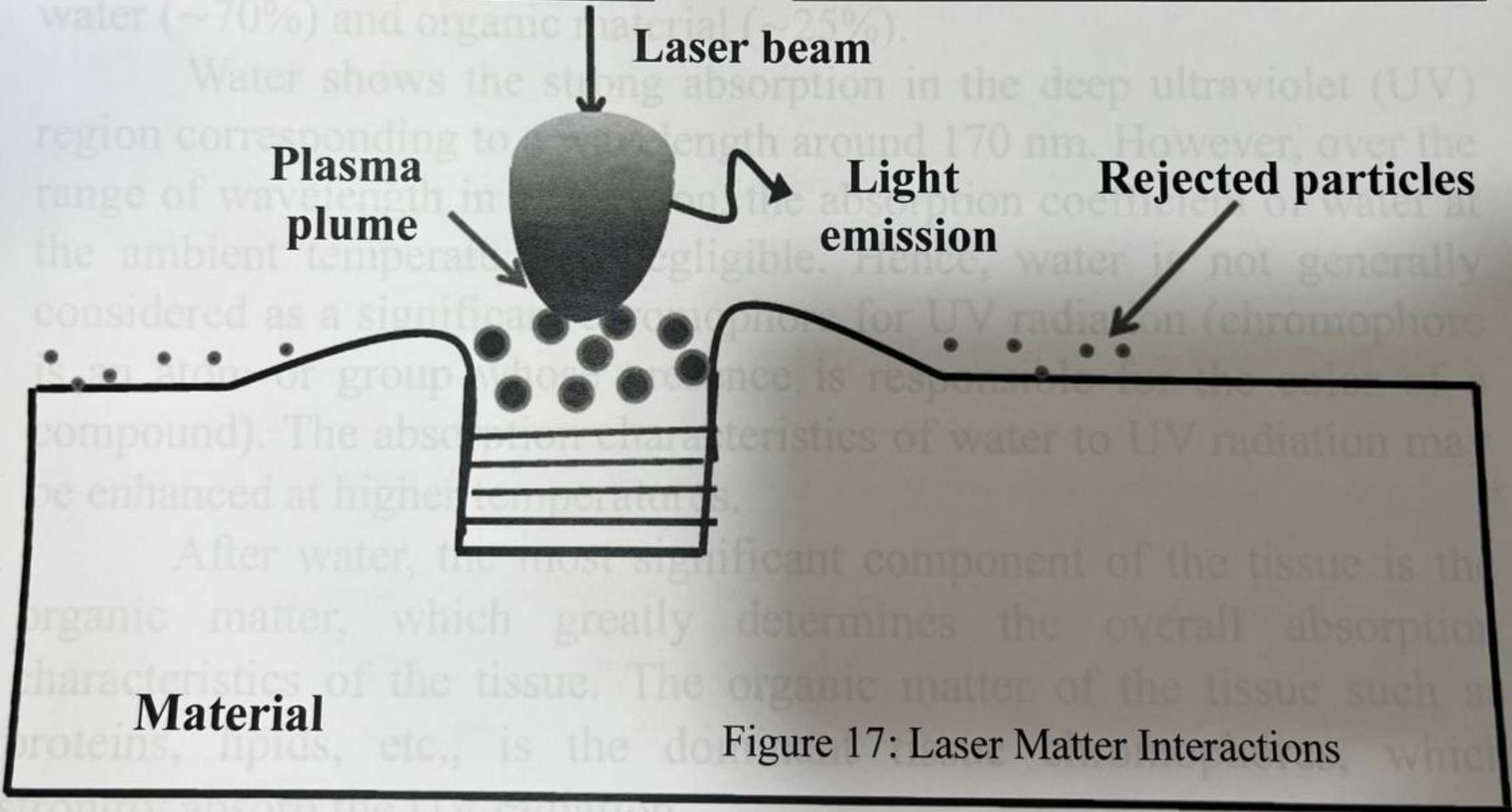- Thermal properties of materials.
- Electrical properties.

Laser beam

Plasma plume

Light emission

Rejected particles

Material

Figure 17: Laser Matter Interactions

Laser Tissue Interactions

The laser tissue interactions are significantly influenced by the composition of the tissue. Biological tissues are primarily composed of water (~70%) and organic material (~25%).

Water shows the strong absorption in the deep ultraviolet (UV) region corresponding to a wavelength around 170 nm. However, over the range of wavelength in UV region, the absorption coefficient of water at the ambient temperature is negligible. Hence, water is not generally considered as a significant chromophore for UV radiation (chromophore is an atom or group whose presence is responsible for the color of a compound). The absorption characteristics of water to UV radiation may be enhanced at higher temperatures.

After water, the most significant component of the tissue is the organic matter, which greatly determines the overall absorption characteristics of the tissue. The organic matter of the tissue such as proteins, lipids, etc., is the dominant tissue chromophores, which strongly absorb the UV radiation.

The absorption of laser radiation by tissue results in laser induced photothermal effects such as tissue heating and vaporization (thermal ablation).

In addition to the thermal effects, the interaction of laser with tissue may be associated with various photochemical and photodisruptive (laser induced breakdown) processes.

These laser tissue interactions depend on;

❖ Properties of the tissue;

➢ Optical properties; coefficients of; reflection, absorption, and scattering, together, they determine the total transmission of the tissue at a certain wavelength.

➢ Thermal tissue properties – such as heat conduction and heat.

❖ laser parameters; wavelength, exposure time, applied energy, focal spot size, energy density, and power density.

Among these, the exposure time is a very crucial parameter when selecting a certain type of interaction.

Although the number of possible combinations for the experimental parameters is unlimited, mainly five categories of interaction types are classified today.

These are;

✓ Photochemical interactions.
✓ Thermal interactions.
✓ Photoablation.
✓ Plasma induced ablation.
✓ Photodisruption.

Figure 18 presents the famous laser tissue interaction map showing the regimes of laser power densities and exposure times for each mechanism. The areas are plotted on the constant energy density lines corresponding to 1 J/cm^2 –1,000 J/cm^2 (Two diagonals show constant energy fluences at 1 J/cm^2 and 1000 J/cm^2, respectively).

This range of laser energy density is most relevant in medical application of lasers.

Figure 18: Laser–tissue interaction map showing the approximate regimes of various interactions in medical applications.
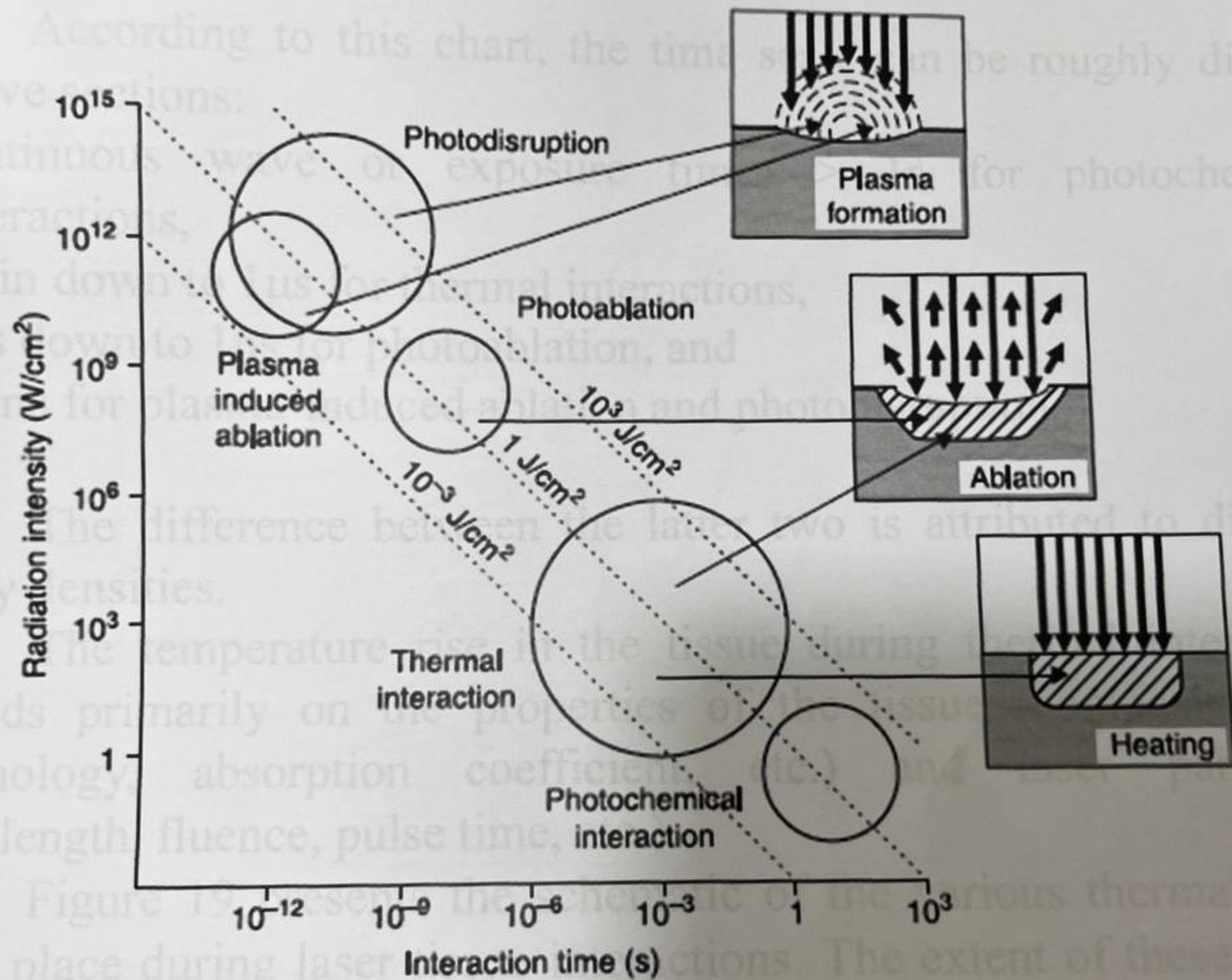
Figure 18: Laser–tissue interaction map showing the approximate regimes of various interactions in medical applications.

According to this chart, the time scale can be roughly divided into five sections:

➢ continuous wave or exposure times $> 1s$ for photochemical interactions,
➢ 1 min down to $1\mu s$ for thermal interactions,
➢ $1\mu s$ down to 1 ns for photoablation, and
➢ < 1 ns for plasma-induced ablation and photodisruption.

The difference between the latter two is attributed to different energy densities.

The temperature rise in the tissue during thermal interactions depends primarily on the properties of the tissue (composition and morphology, absorption coefficient, etc.) and laser parameters (wavelength, fluence, pulse time, etc.).

Figure 19 presents the schematic of the various thermal effects taking place during laser tissue interactions. The extent of these thermal effects is influenced by the temperature distribution in the tissue.
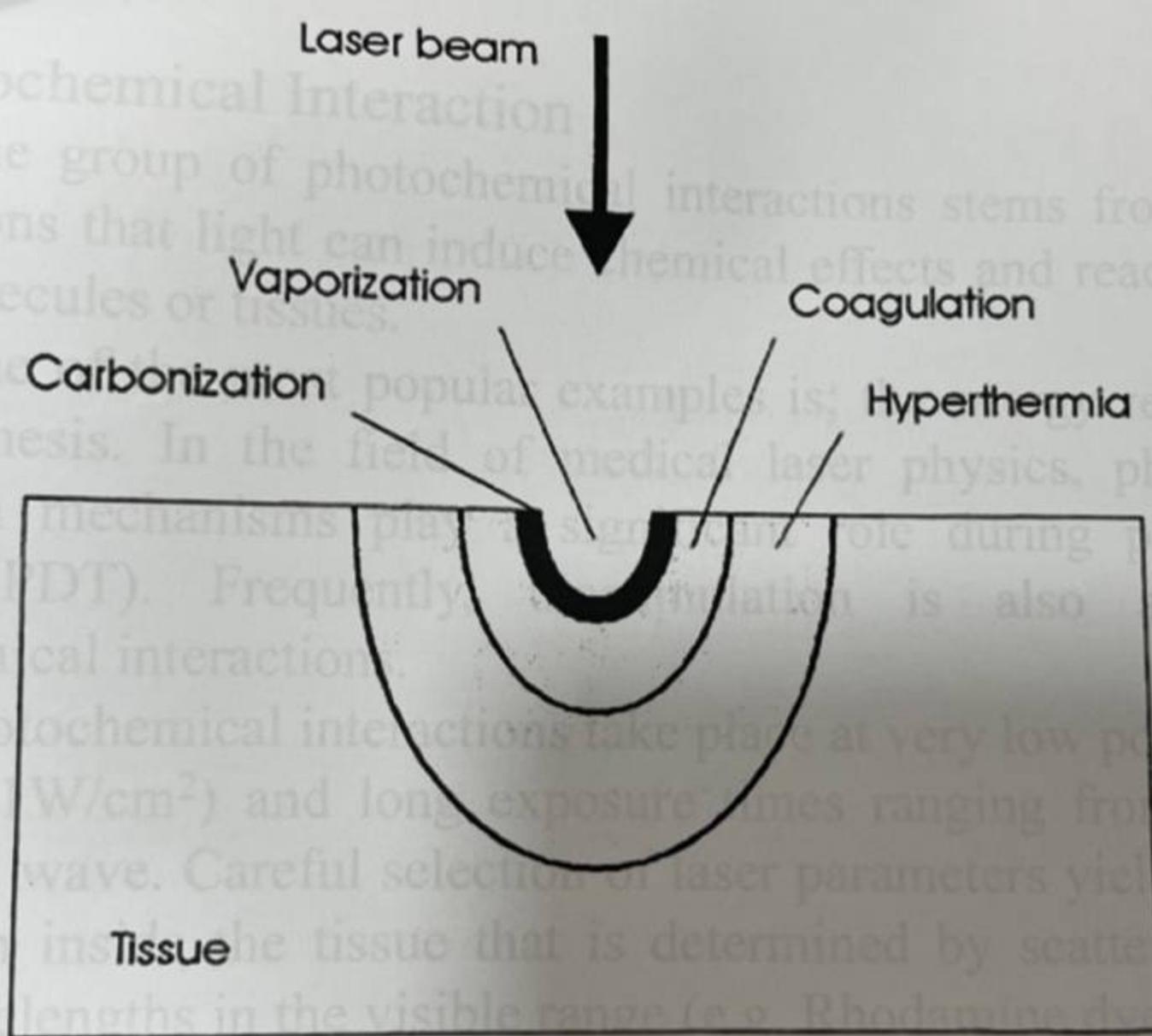
Figure 18: Schematic of various thermal effects during laser–tissue interactions.

❑ Photochemical Interaction

The group of photochemical interactions stems from empirical observations that light can induce chemical effects and reactions within macromolecules or tissues.

One of the most popular examples is; the energy release due to photosynthesis. In the field of medical laser physics, photochemical interaction mechanisms play a significant role during photodynamic therapy (PDT). Frequently, biostimulation is also attributed to photochemical interactions.

Photochemical interactions take place at very low power densities (typically $1 W/cm^2$) and long exposure times ranging from seconds to continuous wave. Careful selection of laser parameters yields a radiation distribution inside the tissue that is determined by scattering. In most cases, wavelengths in the visible range (e.g. Rhodamine dye lasers at 630 nm) are used because of their efficiency and their high optical penetration depths. The latter are of importance if deeper tissue structures are to be reached.

Summary of Photochemical Interaction

❖ Main idea: using a photosensitizer acting as catalyst (only in photodynamic therapy)

❖ Observations: no macroscopic observations

❖ Typical lasers: red dye lasers, diode lasers

❖ Typical pulse durations: 1 s . . . CW

❖ Typical power densities: 0.01 . . . 50W/cm2

❖ Special applications: photodynamic therapy, biostimulation

Thermal Interaction

The term thermal interaction stands for a large group of interaction types, where the increase in local temperature is the significant parameter change.

Thermal effects can be induced by either CW or pulsed laser radiation. While photochemical processes are often governed by a specific reaction pathway, thermal effects generally tend to be nonspecific.

Depending on the duration and peak value of the tissue temperature achieved, different effects like coagulation, vaporization, carbonization, and melting may be distinguished.

Summary of Thermal Interaction

❖ **Main idea:** achieving a certain temperature which lead to the desired thermal effect.

❖ **Observations:** either; coagulation, vaporization, carbonization or melting.

❖ **Typical lasers:** CO_2, Nd:YAG, Er:YAG, Ho:YAG, argon ion and diode lasers.

❖ **Typical pulse durations:** 1 μs . . . 1min.

❖ **Typical power densities:** 10 . . . 10^6 W/cm².

❖ **Special applications:** coagulation, vaporization, melting, thermal decomposition, treatment of retinal detachment, laser-induced interstitial thermotherapy.

Photoablation

Photoablation was identified as ablative photodecomposition, meaning that material is decomposed when exposed to high intense laser irradiation.

Typical threshold values of this type of interaction are 10^7–10^8 W/cm^2 at laser pulse durations in the nanosecond range.

The ablation depth, i.e. the depth of tissue removal per pulse, is determined by the pulse energy up to a certain saturation limit.

The geometry of the ablation pattern itself is defined by the spatial parameters of the laser beam.

Summary of Photoablation

❖ Main idea:
  direct breaking of molecular bonds by high energy UV photons.

❖ Observations:
  very clean ablation, associated with audible report and visible fluorescence.

❖ Typical lasers:
  excimer lasers, e.g. ArF, KrF, XeCl, XeF.

❖ Typical pulse durations:
  $10 \ldots 100$ ns.

❖ Typical power densities:
  $10^7 \ldots 10^{10}$ W/cm^2.

❖ Special applications:
  refractive corneal surgery.

Summary of Plasma-Induced Ablation

- ❖ **Main idea:** ablation by ionizing plasma formation.
- ❖ **Observations:** very clean ablation, associated with audible report and bluish plasma sparking.
- ❖ **Typical lasers:** Nd:YAG, Nd:YLF, Ti:Sapphire.
- ❖ **Typical pulse durations:** 100 fs . . . 500 ps.
- ❖ **Typical power densities:** 10^{11} . . . 10^{13} W/cm^2
- ❖ **Special applications:** refractive corneal surgery, caries therapy.