Laser-ablated silicon nanoparticles in tumor treatment via hyperthermia: numerical calculations

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The advantages of using silicon nanoparticles (SiNPs) obtained by ablation of porous silicon for hyperthermia treatment

- **Definition of hyperthermia:** increase in body temperature in the range 41-45˚C that causes changes in blood flow in tumor tissue that can either increase the efficiency of other treatment methods or lead to tumour cell death itself.
- **SiNP size**: less than 100 nm, ensures SiNPs penetration in biotissues and further release from the organism

Alternative fabrication techniques such as mechanical milling or ultrasonic grinding of porous silicon matrices allow to produce SiNPs of micron diameter.

- **SiNP chemical purity and safe excretion:** SiNPs degrade readily in biological environments to form silicic acid, which is a natural trace compound in humans.

Gold NPs are chemically inert that complicates their excretion.

- **SiNP concentration in tissue**: 5 mg/ml. SiNPs could penetrate into the cells without any cytotoxic effect up to the concentration of 100 mg/mL.
- **Localized heating :** *decreases side effects comparing to the whole-body hypertermia*

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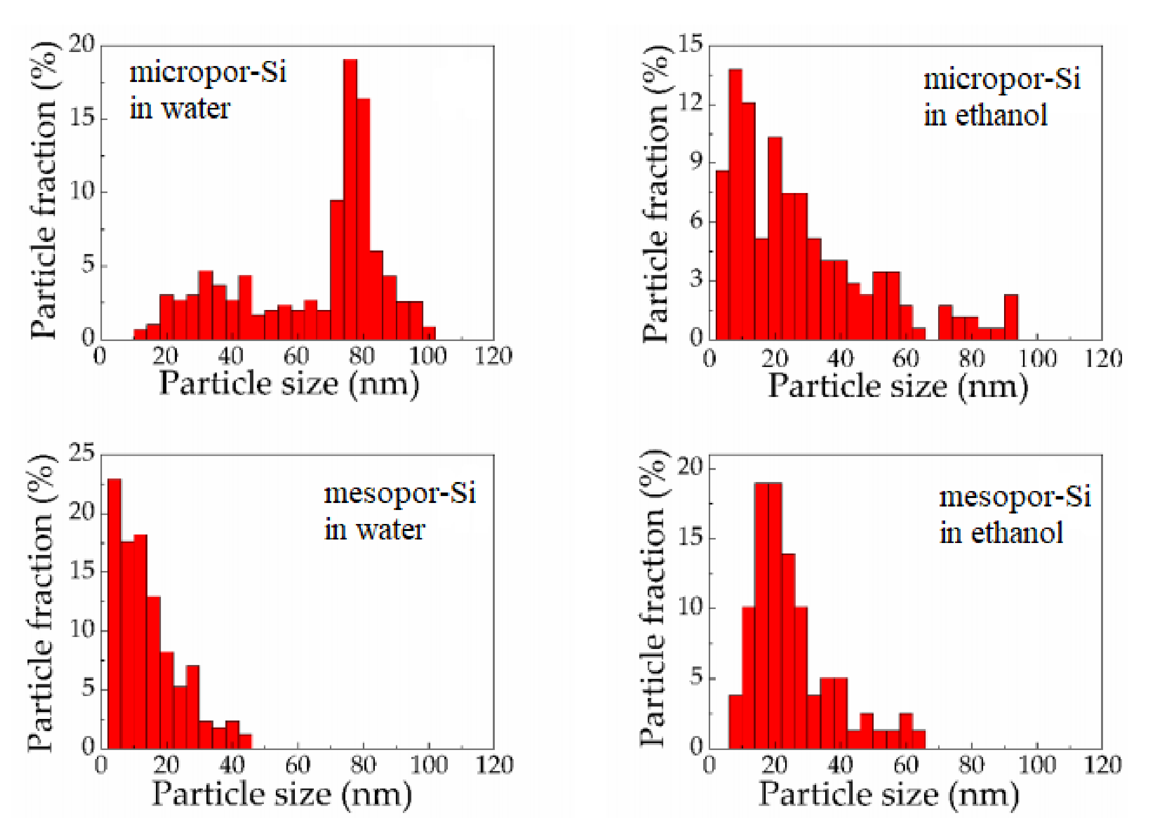
Nanoparticles formed by porous silicon laser ablation: size, scattering & absorption properties



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From spectrophotometry measurements:
Wavelengths 633 and 800 nm

$\mu_t \sim 1\text{-}3\ cm^{-1}$

$\mu_a \sim 0.02\text{-}0.6\ cm^{-1}$

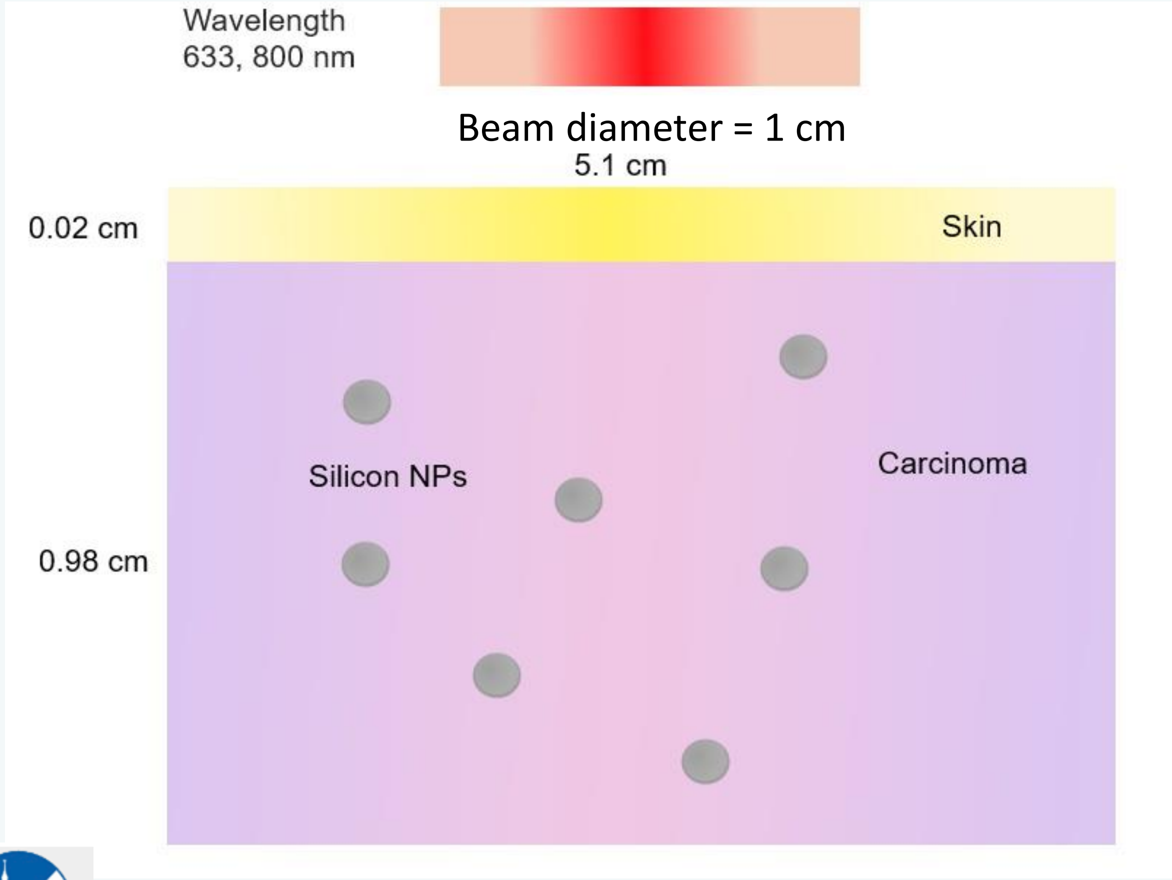
$g \sim 0.05\text{-}0.3$

Concentration 0.5 mg/ml

d < 100 nm => effective penetration in a biological tissue

Adding NPs suspension to a tissue: increase in scattering and absorption of red (633 nm) and infrared (800 nm) radiation

P = 500 mW/cm^{2}, continuous-wave

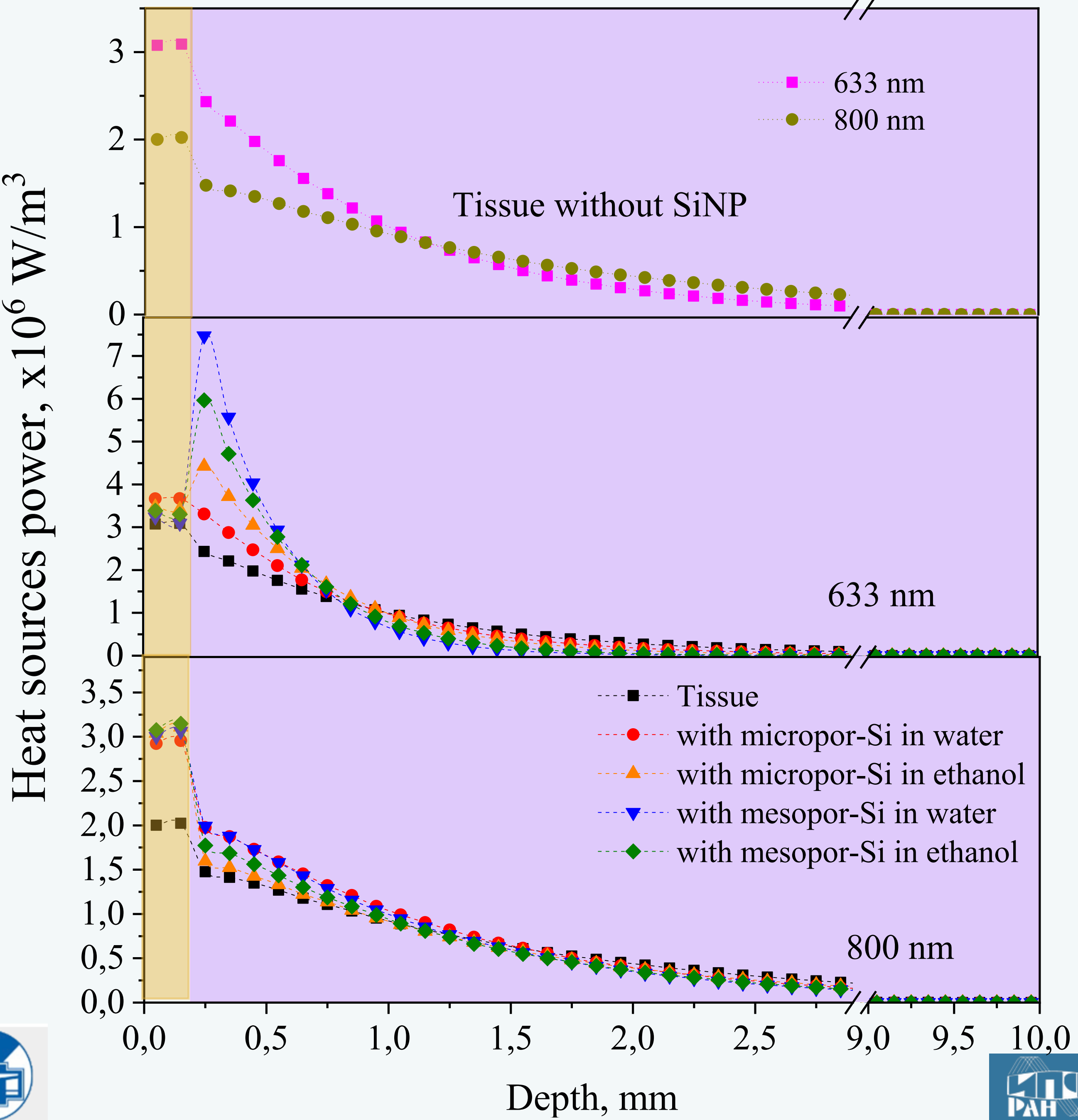


NPs concentration in tissue: 5 mg/ml

	Tissue	Tissue + NP
	633 nm	
μ_t, cm^{-1}	151.7	161.9 ÷178.9
μ_a, cm^{-1}	1.7	2.5÷5.4
	800 nm	
μ_t, cm^{-1}	100.9	106.7÷113.7
μ_a, cm^{-1}	0.9	1÷1.3

Monte-Carlo calculation results:
Voxel size 1 x 1 x 0.1 mm

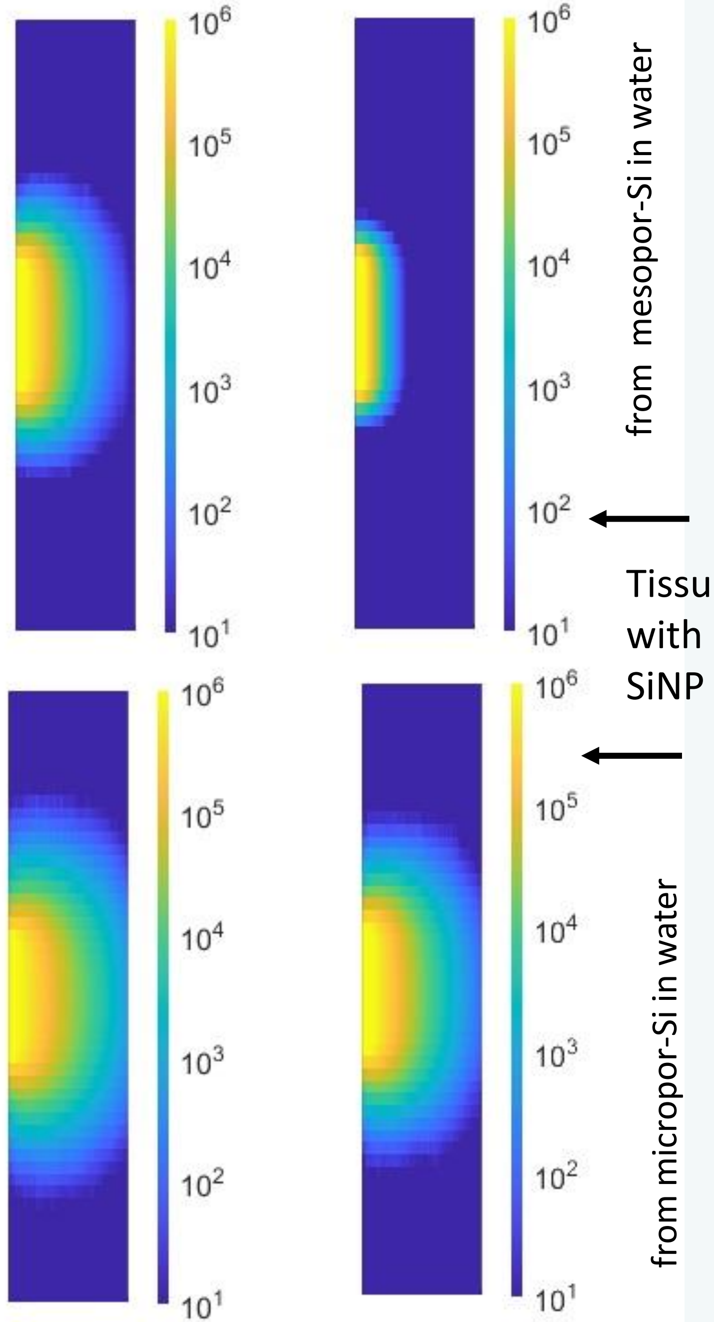
SiNP modifying absorption



λ= 633 nm

Tissue without particles

λ=800 nm



Bioheat equation and its boundary conditions

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q_{perf} + Q_{met} + Q_{ext}$$

k – thermal conductivity, 0.37 W/m*K

Q_{perf} is convective cooling of blood perfusion, = $\rho_{blood} \cdot C_{blood} \cdot \omega_{blood} \cdot (T_{blood} - T)$

Q_{met} is metabolic heat generation per unit volume, 420 W/m^3

Q_{ext} is distributed volumetric heat source due to tissue's light absorption, [W/m^3]

Convection on boundary skin-air:

$$-c \frac{\partial T(0,t)}{\partial z} = h\left(T_{air} - T(0,t)\right) = hT_{air} - hT(0,t)$$

h – heat transfer coefficient, 18 W/m^2

T_{air} = 298K

Constant temperature at inner boundaries:

T_{body} = 310K

Solved in COMSOL Multiphysics package, using finite-element method

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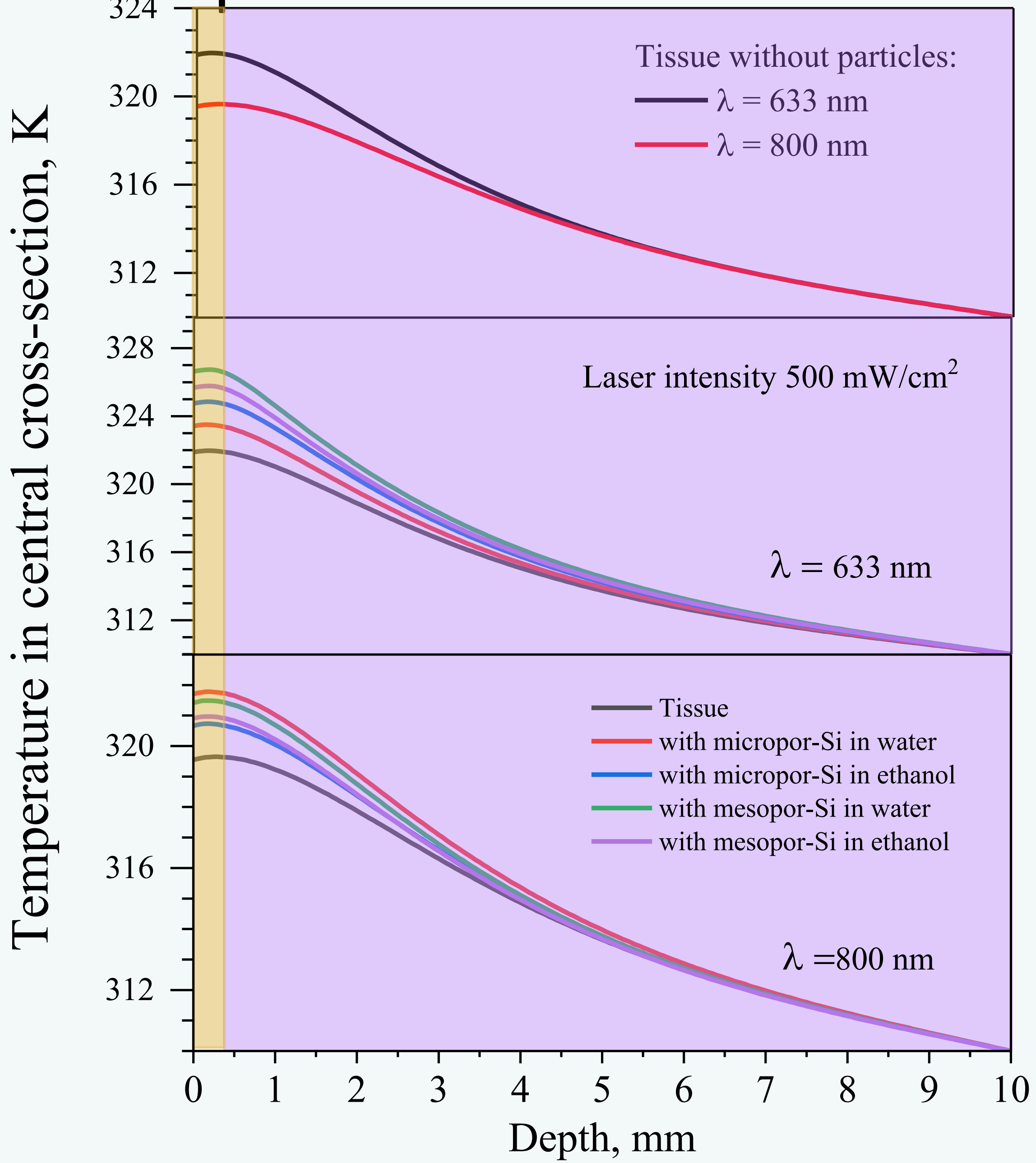
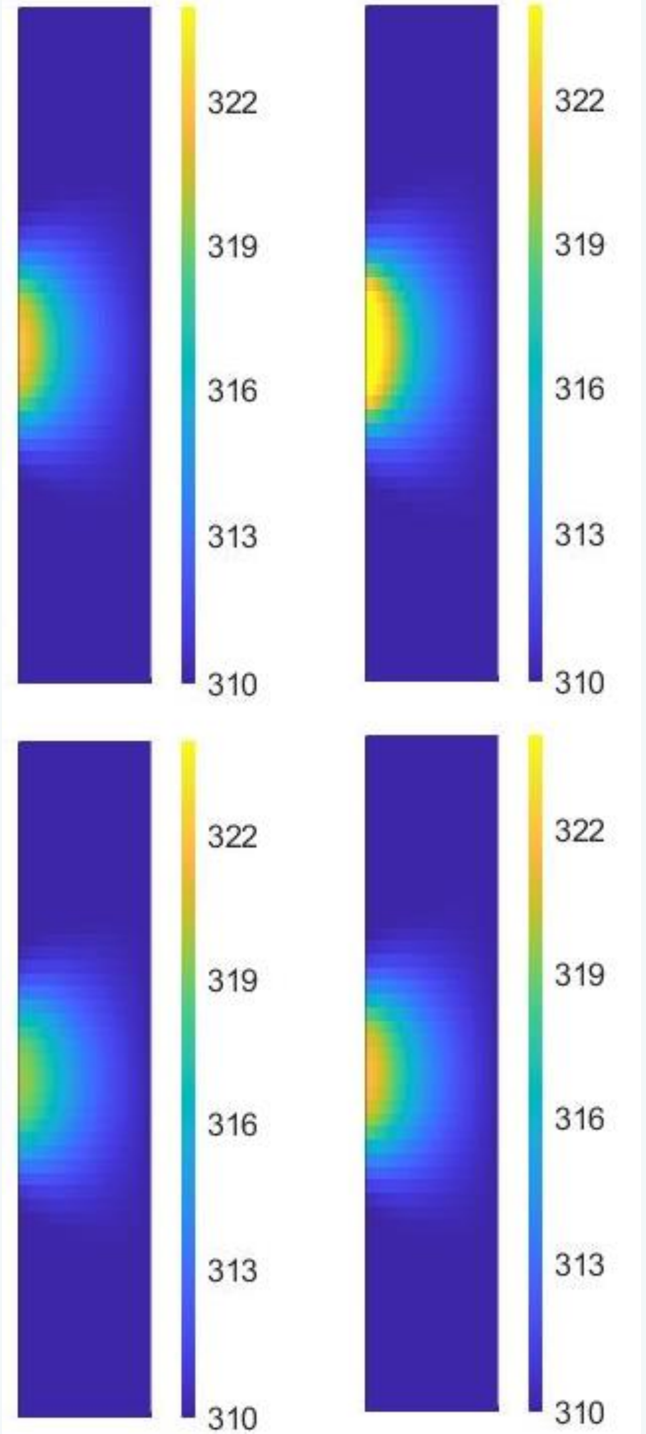
Temperature distributions



λ= 633 nm

λ= 800 nm

Without SiNP

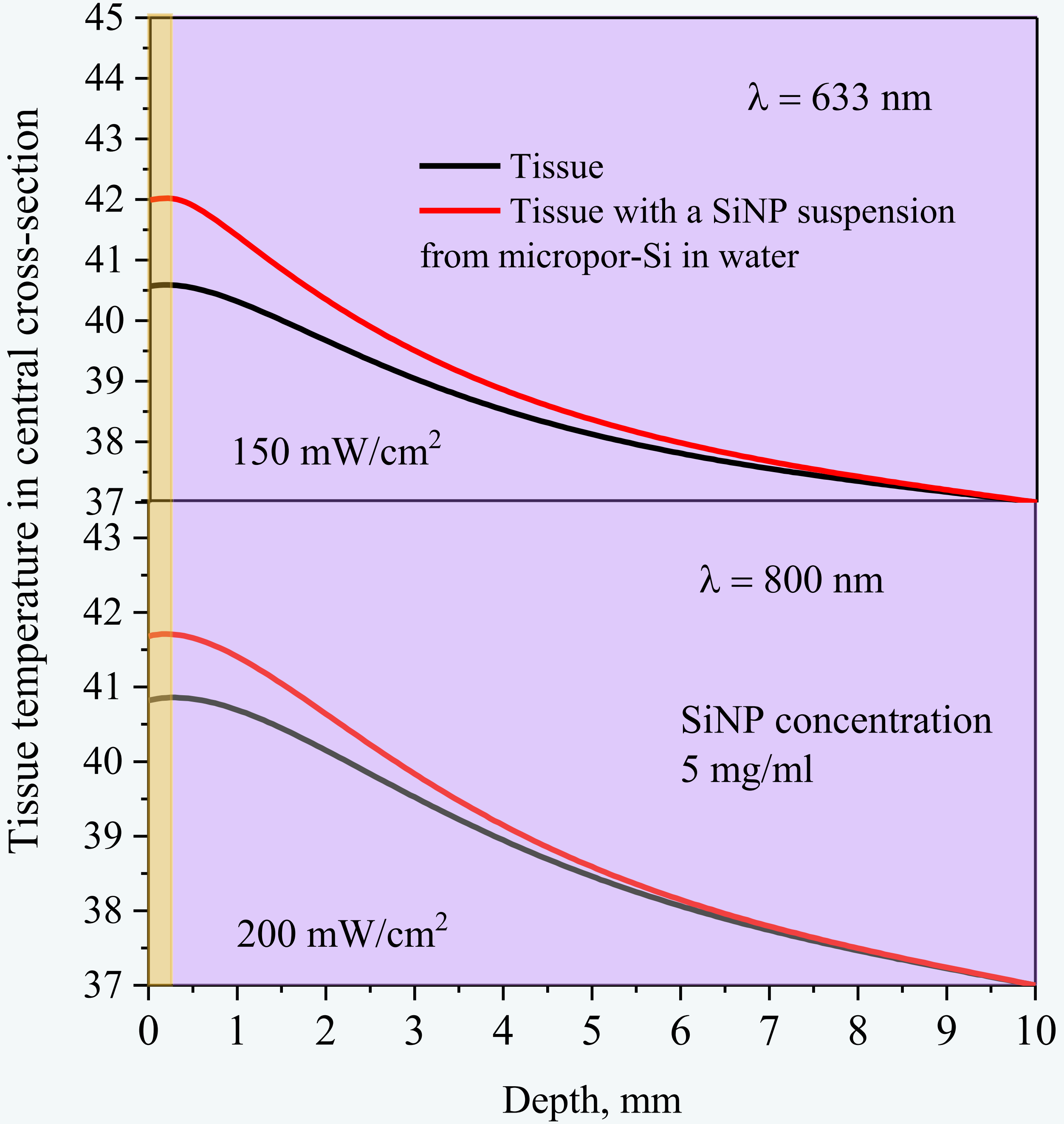


With SiNP

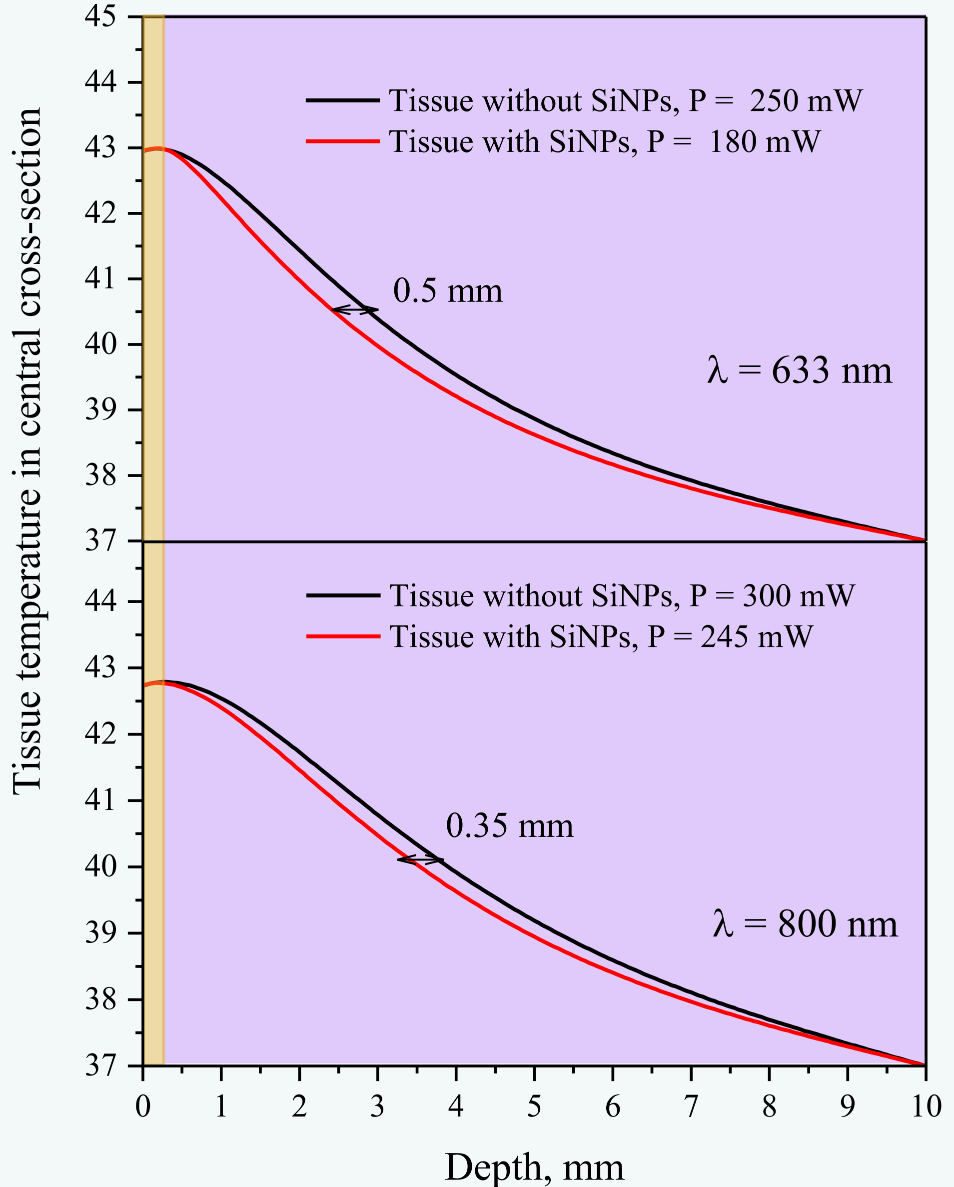
Suggestion for photothermal therapy with SiNPs

<u>Without particles:</u>
tissue temperature is lower than 41 ˚C.

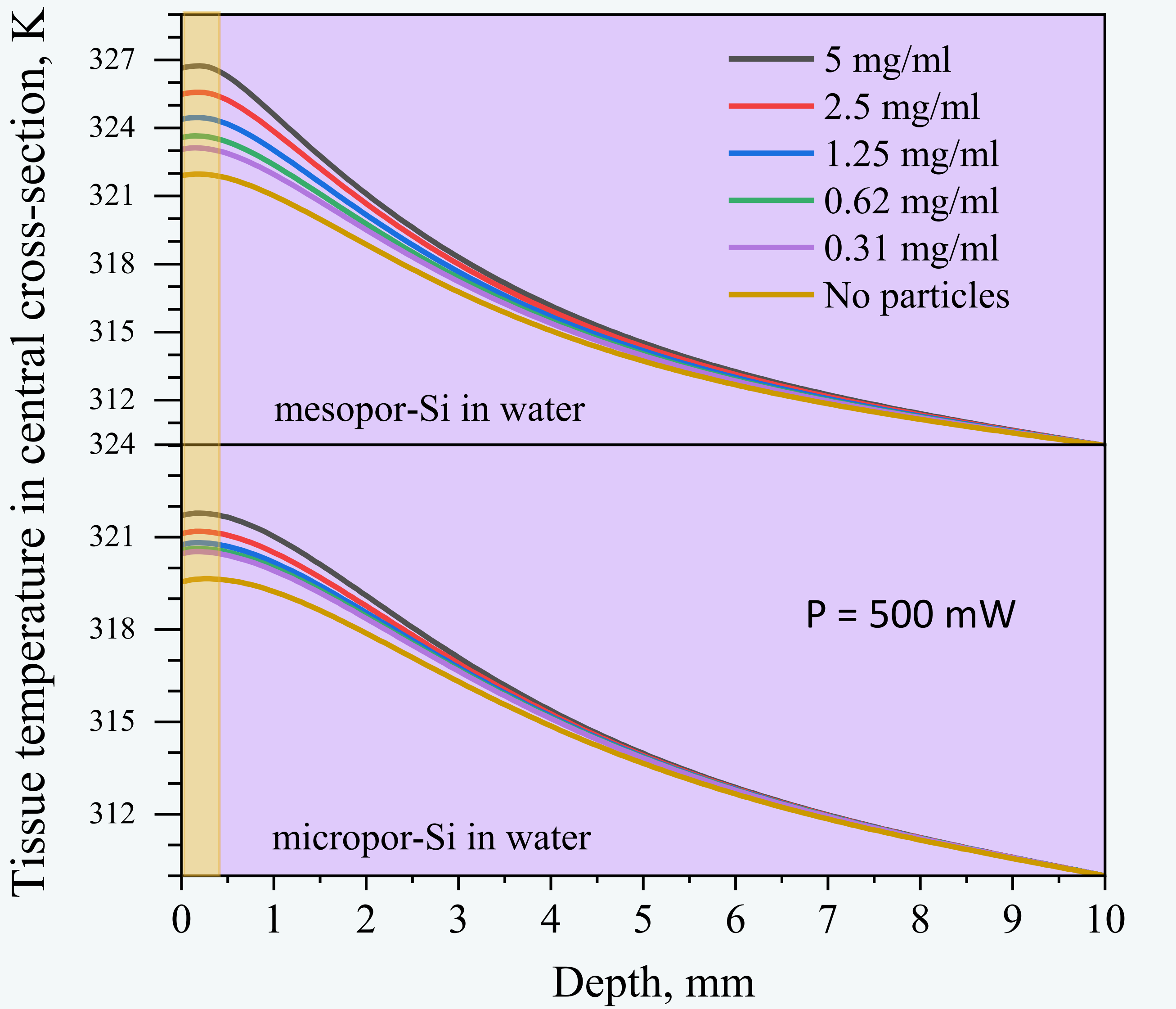
<u>With particles:</u>
at the same laser power
hyperthermia temperatures are achieved.



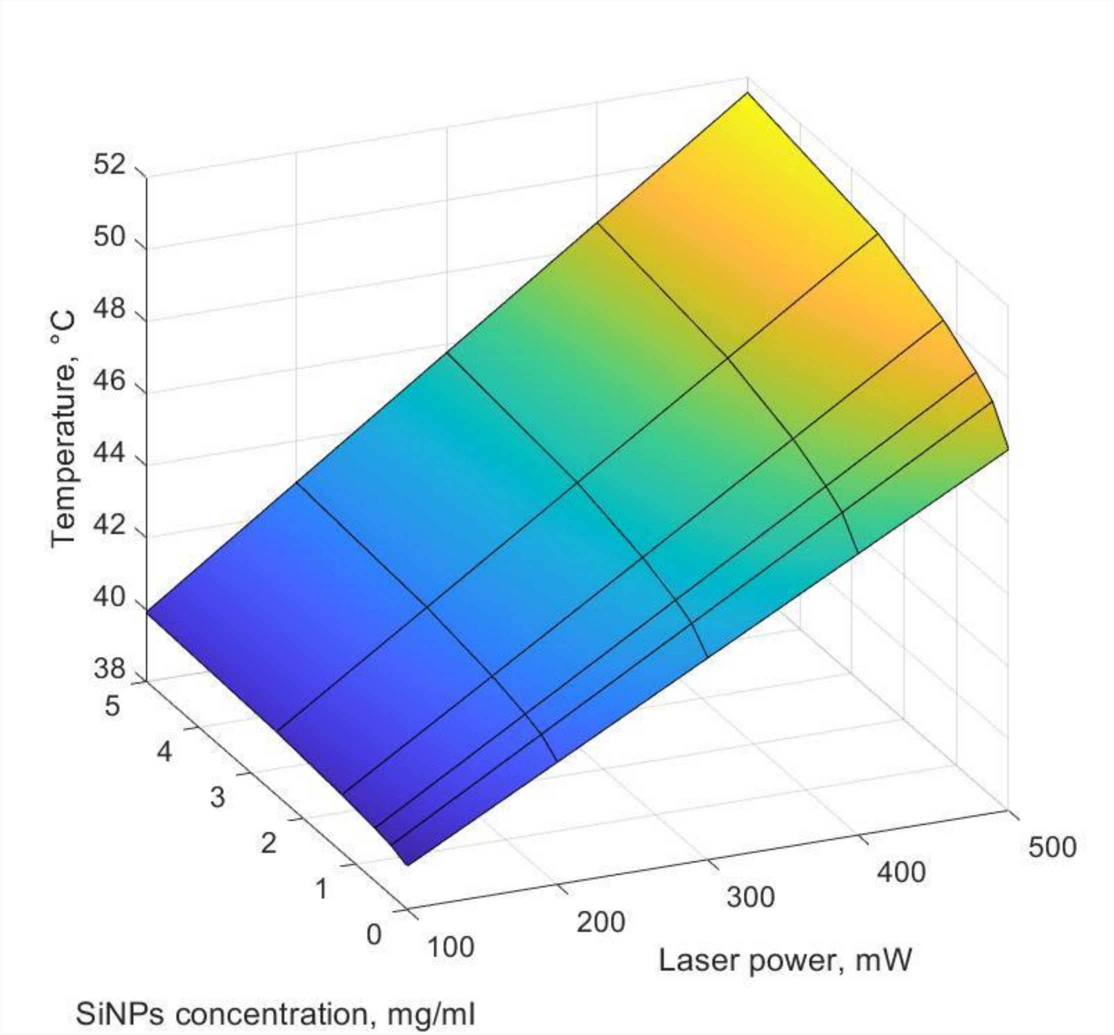
Heating localization at SiNP concentration 5 mg/ml

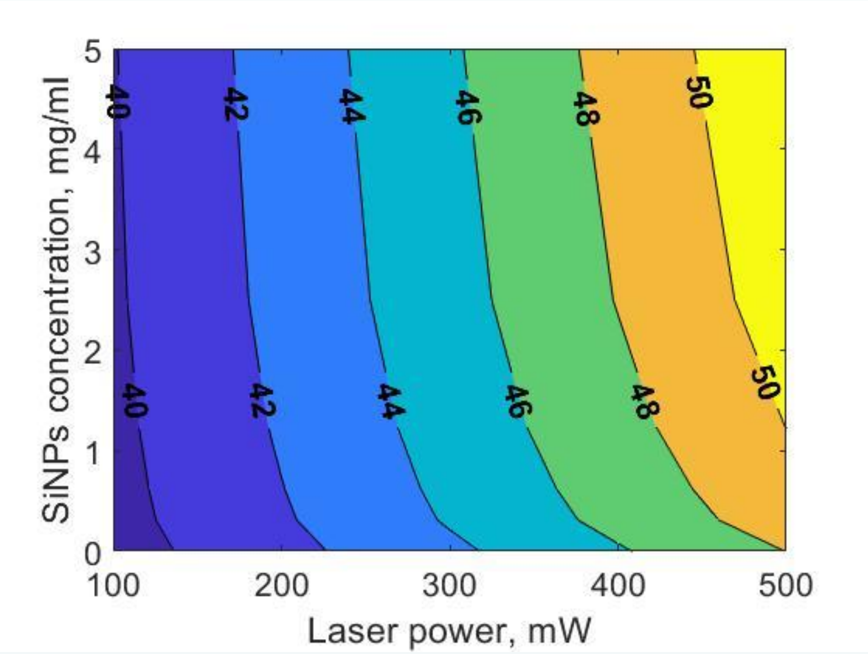


Temperature depth distribution dependence on SiNPs concentration



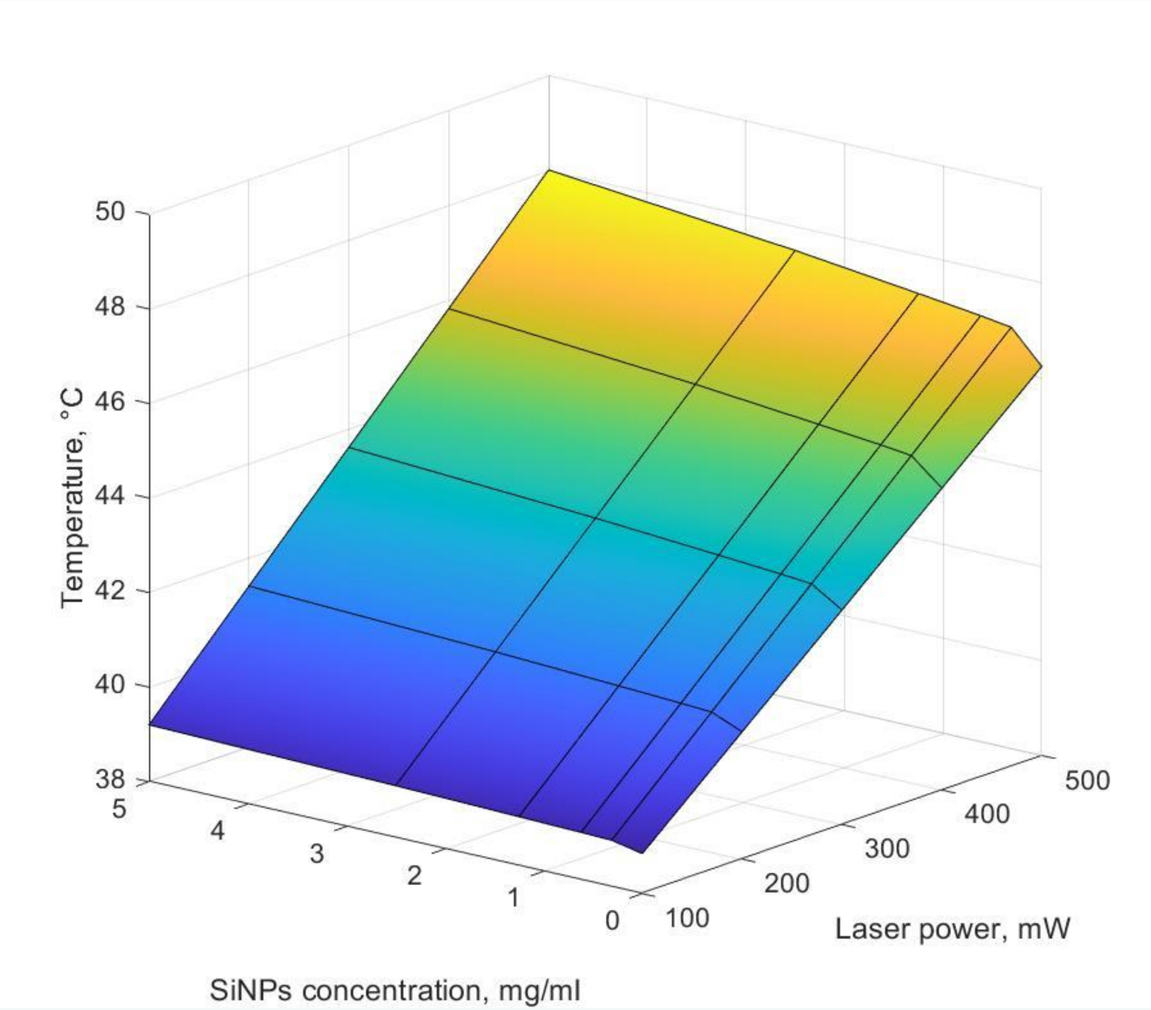
Dependance of temperature on laser wavelength, power and SiNP concentration, λ = 633 nm

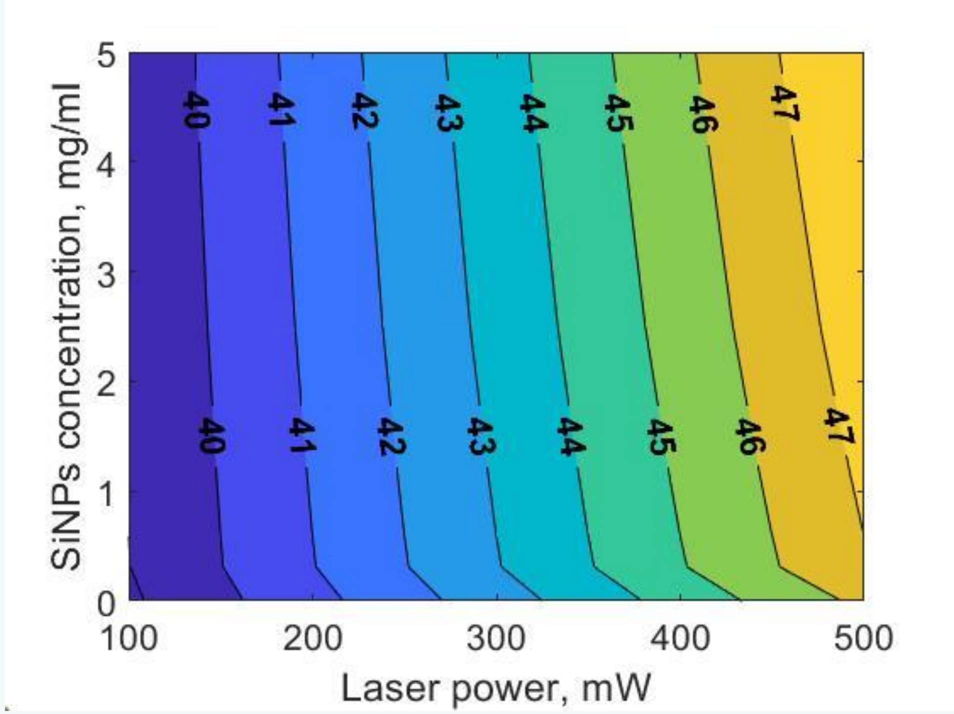




Isothermal contours

Dependance of temperature on laser wavelength, power and SiNP concentration, λ = 800 nm





Isothermal contours

Conclusions

- It is possible to achieve up to double increase in heat sources density in near-surface regions: SiNP embedded in tissue increase its scattering and absorption.
- The best ablation targets in the sense of hypertermia application are: for wavelength 633 nm – mesoporous silicon in water, for wavelength 800 nm - microporous silicon in water;
- It is shown that in tumor tissue temperature-depth profile narrows even by small concentrations of SiNPs (5 mg/ml)
- it is possible to achieve 2– 5 K increase in maximum temperature in comparison with the tumor without nanoparticles depending on the illumination wavelength and type of ablation target in the course of the nanoparticles fabrication.
- Simulations indicate that the temperatures required for hyperthermia (~ 42°C) can be reached at laser intensities 150 and 200 mW/cm^2 for illumination wavelengths 633 and 800 nm, respectively.

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