Laser surface processing for biomedical applications

L. Orazi

VI International Conference «TOPICAL ISSUES OF THEORETICAL AND CLINICAL MEDICINE
SUMY - 18/10/2018

DISMI @ University of Modena and Reggio Emilia

NANOSURF

MIcro Quantum Dot-Light Emitting Diode/Organic Light Emitting Diode - DIrect patterning

acheon

CROP

DESERVE

ECHORD

MIRANDELA

UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

i-Sur

smartCEM

PAN ROBOTS
Plug&Navigate robots for smart factories

END

ascens
autonomic service-component ensembles

NANOFUNCTION

STRATOS
open System for TRActOr autonomous operationS

MAAT

UNIFARM

sfor
sistema formativo riuso

- 65 permanent staff
- ≈ 100 collaborators
- Management and Production Engineering
- Mechatronics
- Professional Industrial Engineering
- 5 spin off

CIGS - Central Interdepartmental Laboratory

- About 8 M€ state of the art instruments
- 8 people highly trained staff
- SEM, TEM, AFM, XRD, NMR, EPR, mass-spectroscopy, Q-TOF, Confocal microscopy

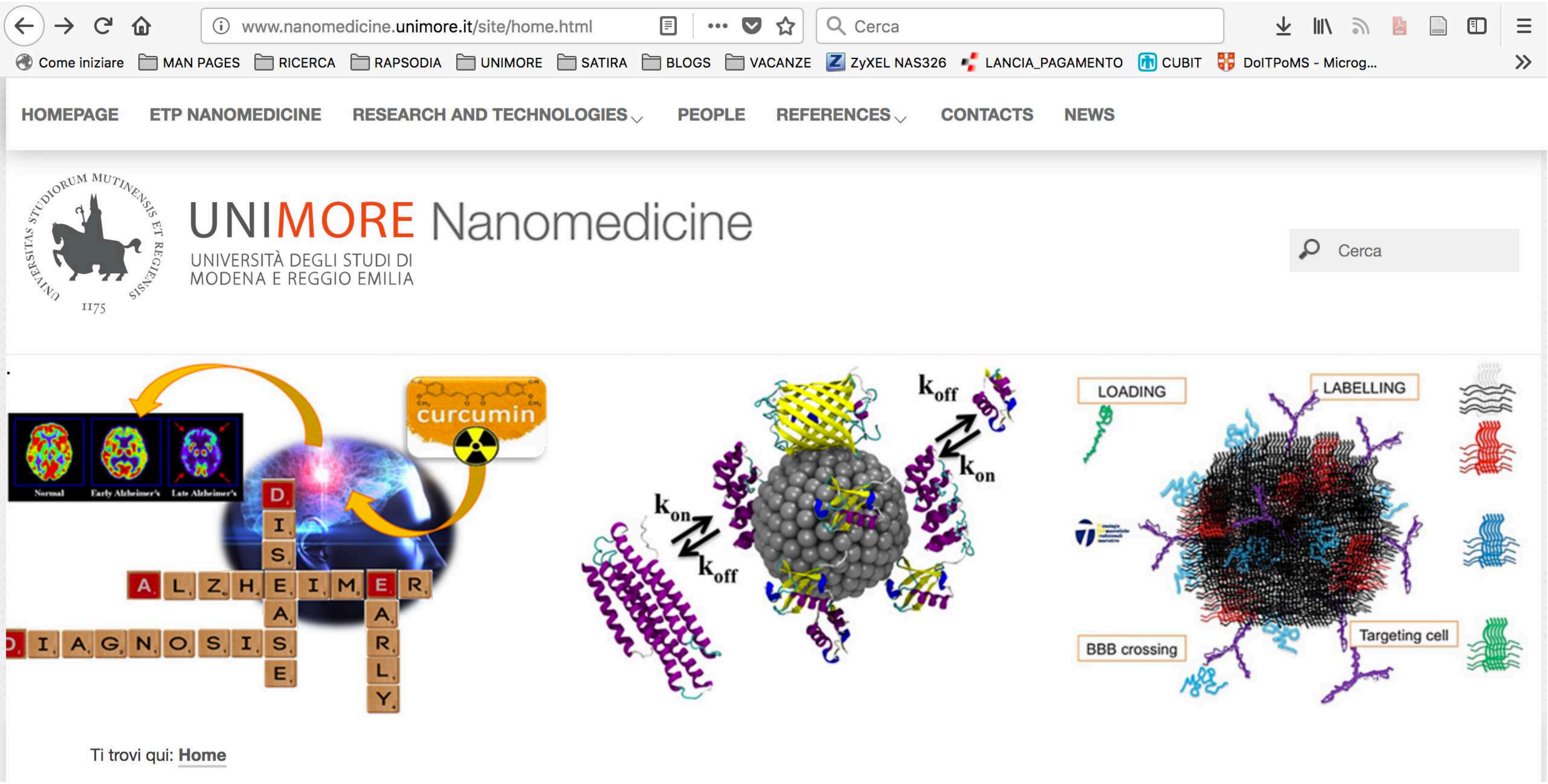
UNIMORE UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA
CIGS - Centro Interdipartimentale Grandi Strumenti







Nanomedicine @ UNIMORE



Manufacturing and Technology Group @ DISMI

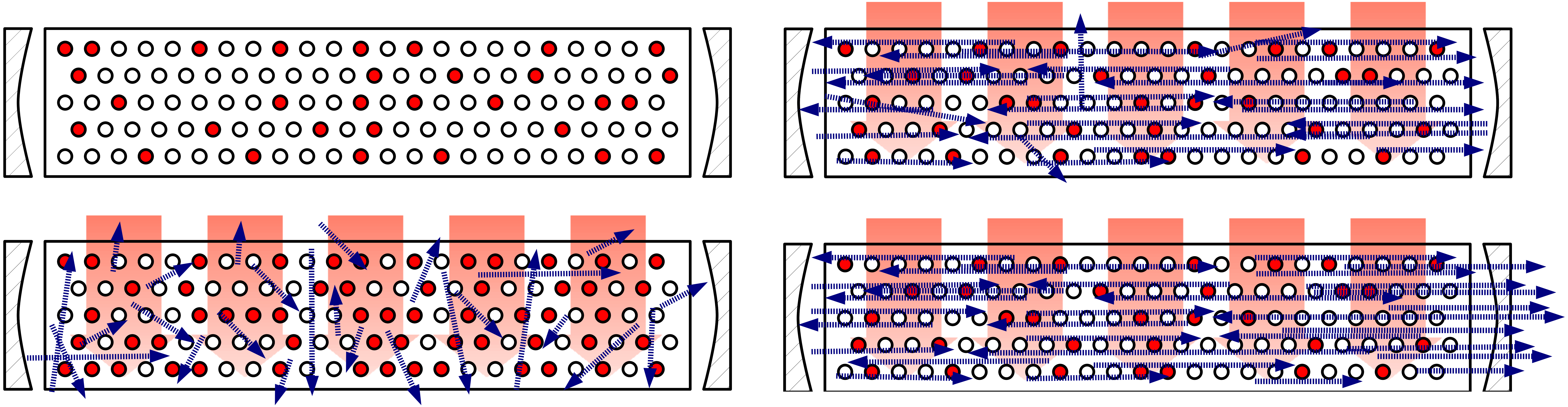
Small but growing group…

- Prof. Leonardo Orazi
- Prof. Barbara Reggiani
- Dr Iaroslav Gnilitskyi
- Dr Michele Cotogno
- PhD students
  - Riccardo Pelaccia
  - Mohamed Darwish

Main research activities

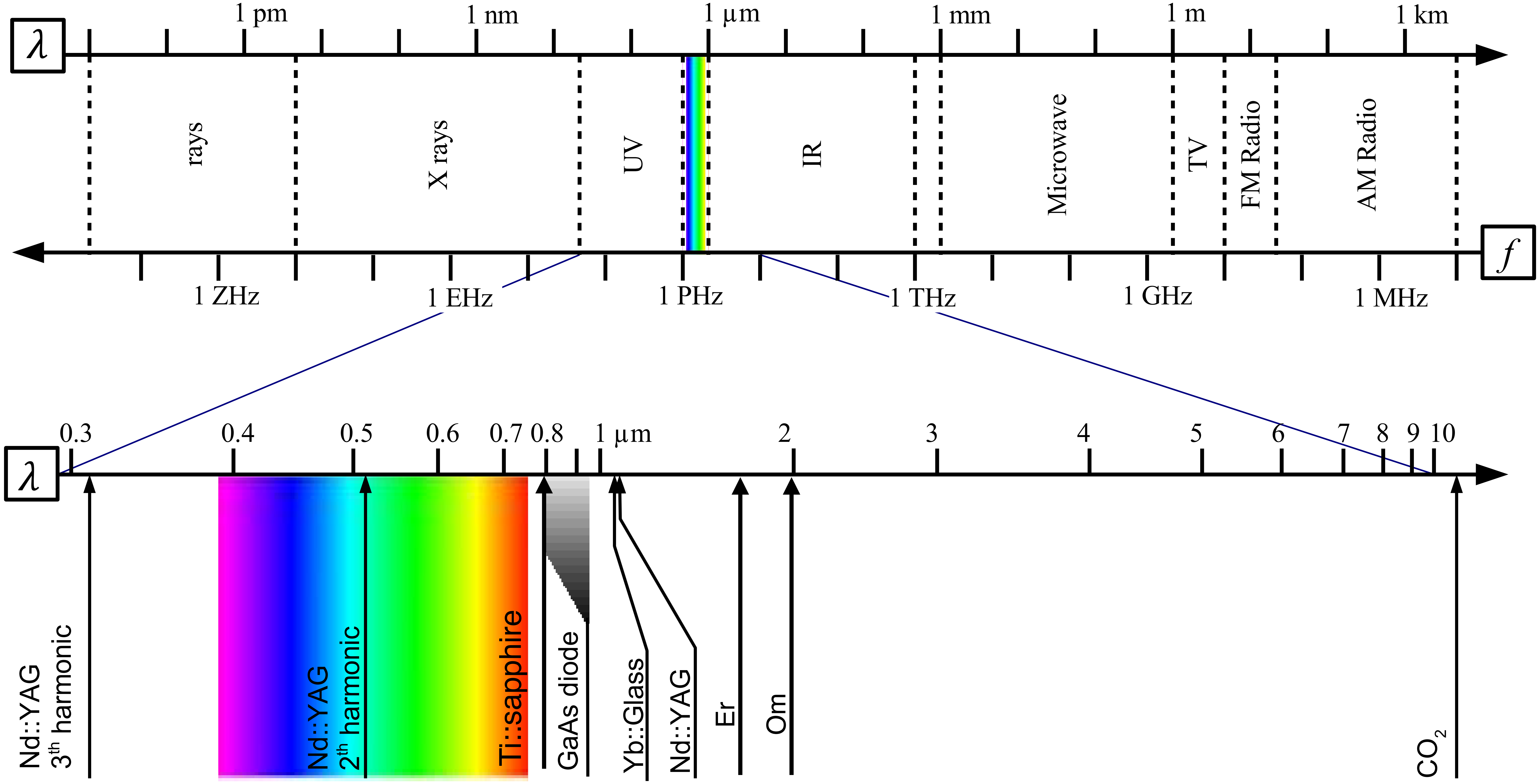
- Laser based processing
- CAD CAM - programming
- Numerical Simulation of Manufacturing Processe

LASER: Light Amplification by Stimulated Emission of Radiation.

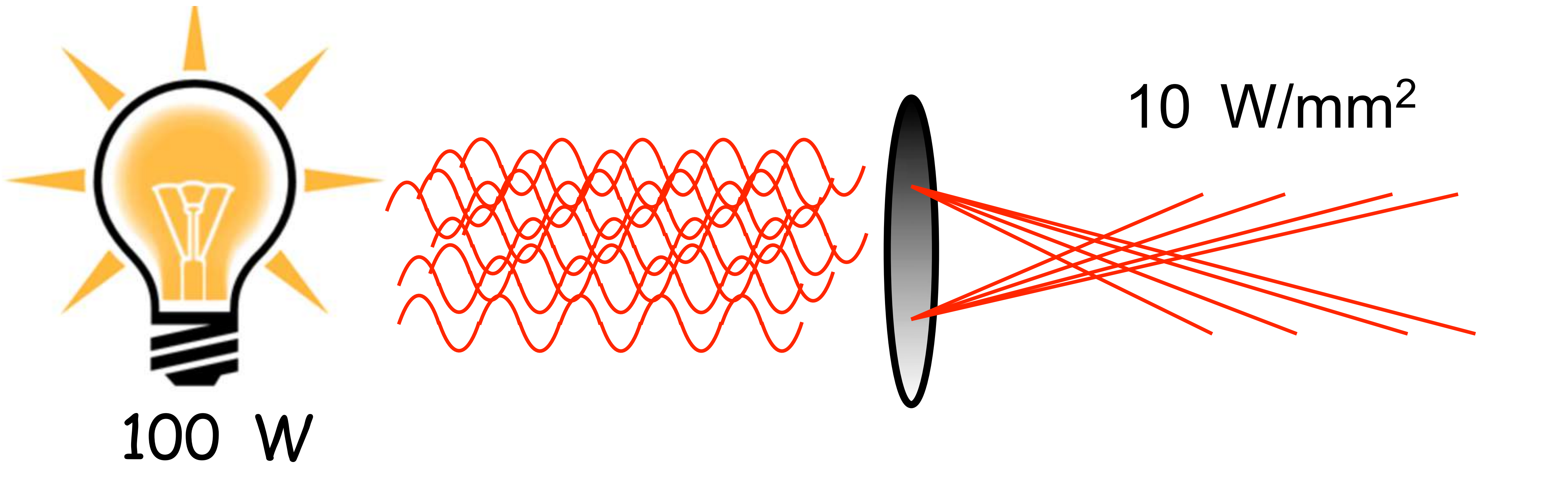


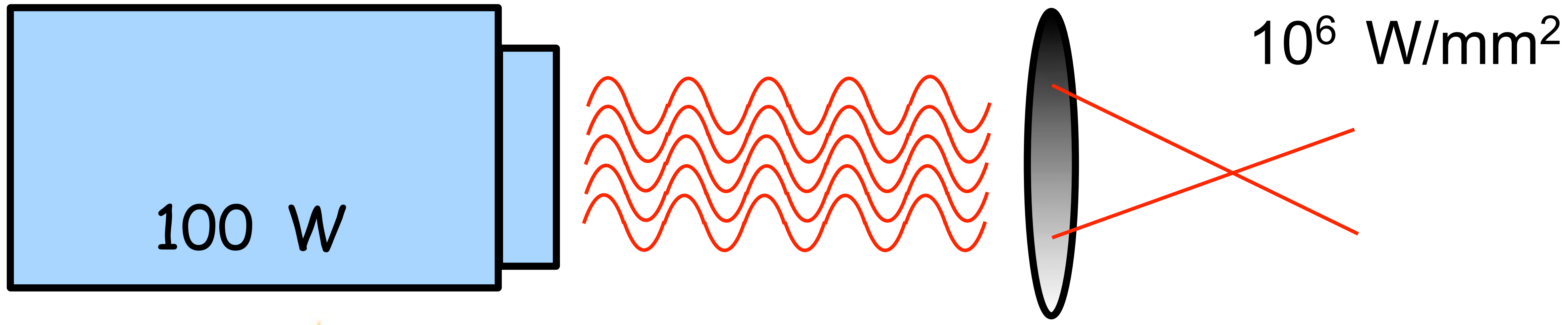
- An appropriate media able to photoluminescence is pumped by a source of energy
- The generated photons stimulate the photoluminescense in phase of already activated matter
- A partial reflective mirror emits the highly focusable laser beam
- Active media can be atom of molecules in gases, ions in solid crystals or semiconductor
- Energy can be pumped as electric field, incoherent light (lamps/diodes) or coherent light (other lasers)

LASER: wavelength

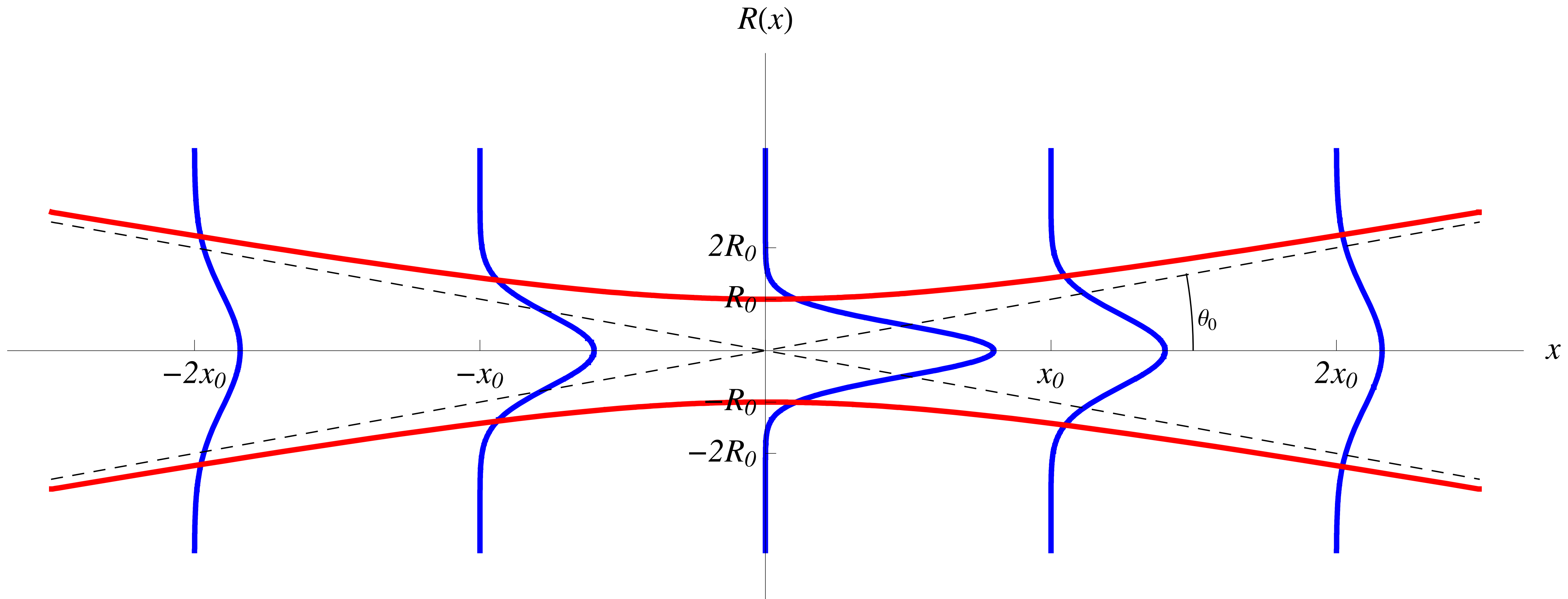


LASER: spatial distribution



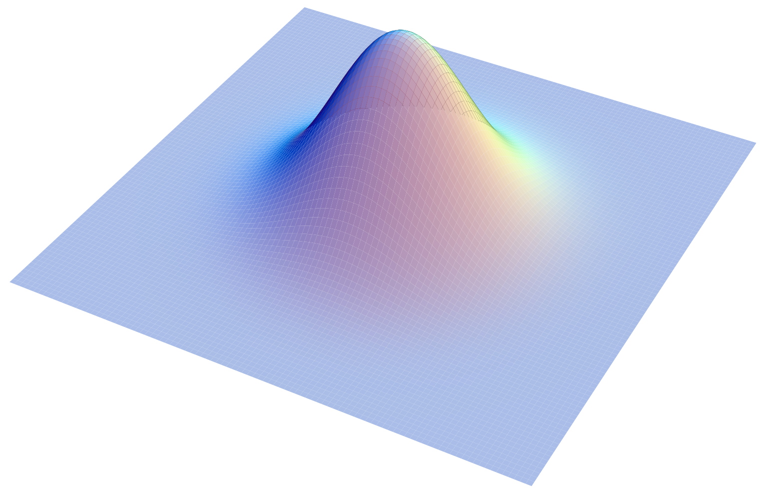


Beam Popagation
The rectilinear propagation of laser beams only in **SCI-FI movies**.
Why? Only an **infinite** EM planar wave is a solution of the Maxwell equation.
Another solution is the **gaussian** beam that propagates parabolically.
Minimum focal size is limited by **diffraction**



Intensity: specific power, power over surface, heat flux [**W/m²**]
It influences the temperature on the material
It drive thermal processes

Fluence: specific energy, energy over surface, [**J/m²**]
Photons accumulated on the surface
It drives photochemical processes



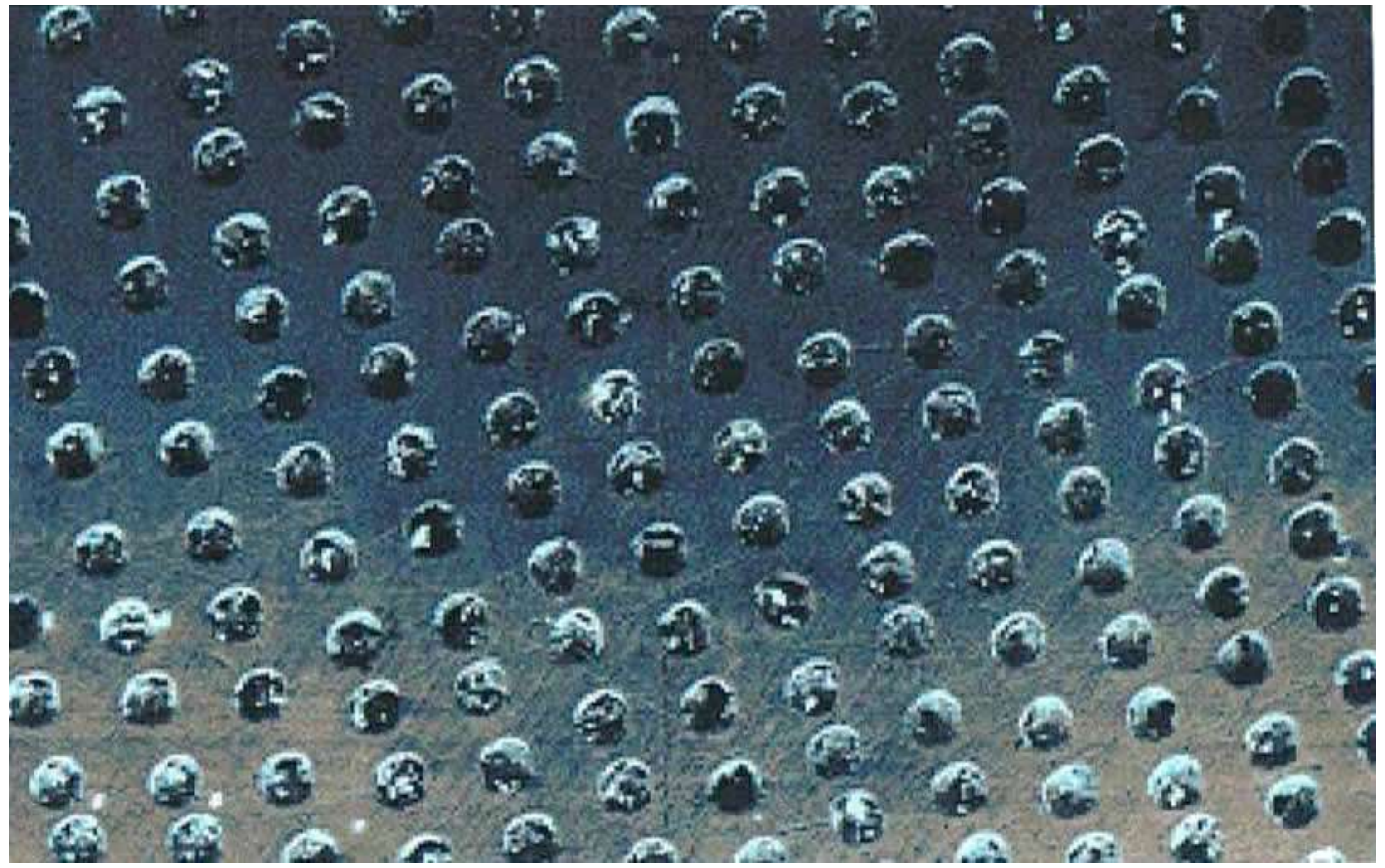
$$d_{min} = \frac{4}{\pi}\lambda\frac{f}{D}$$

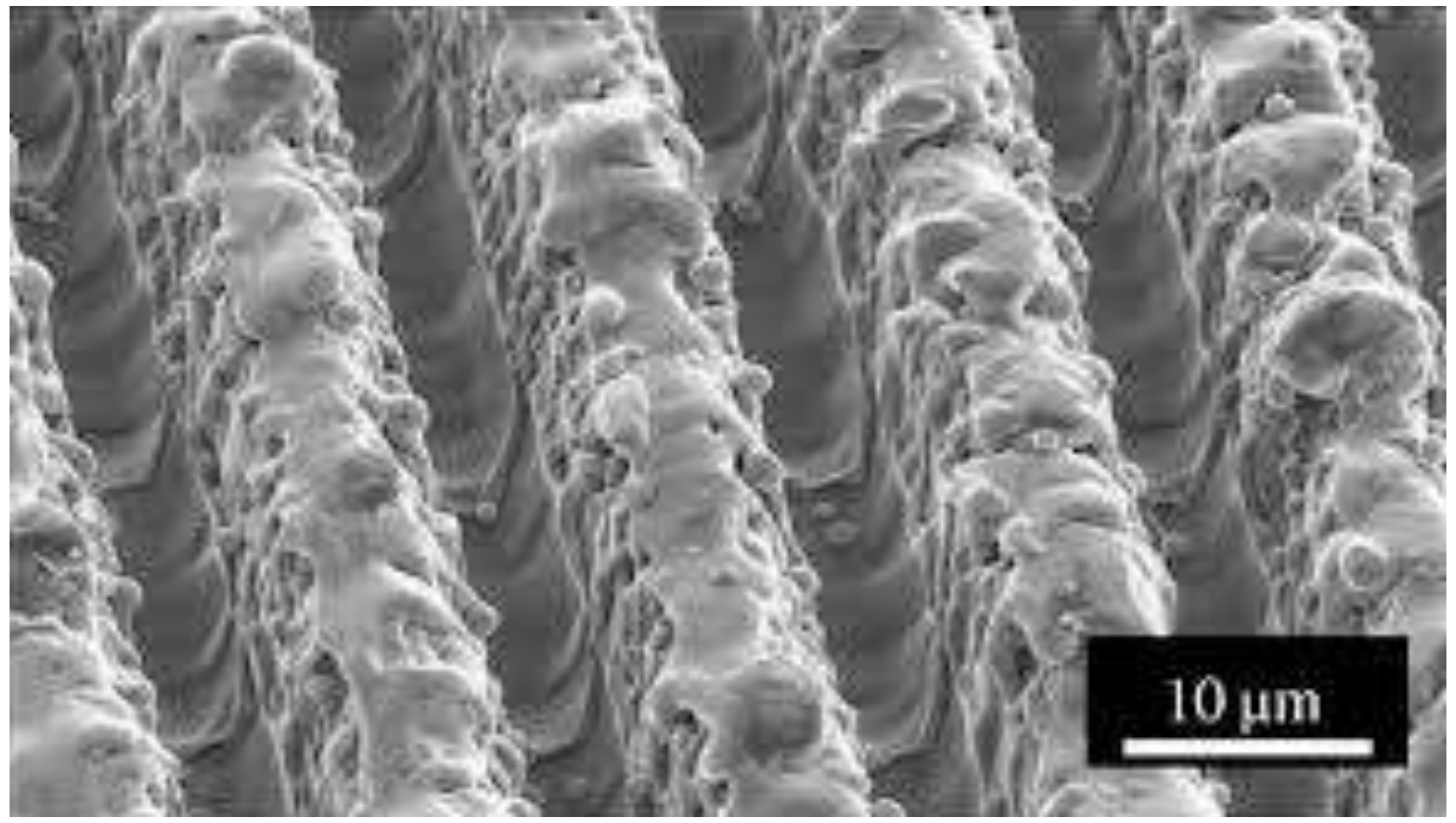
λ: laser wavelength
f: focal distance
D: lens diameter

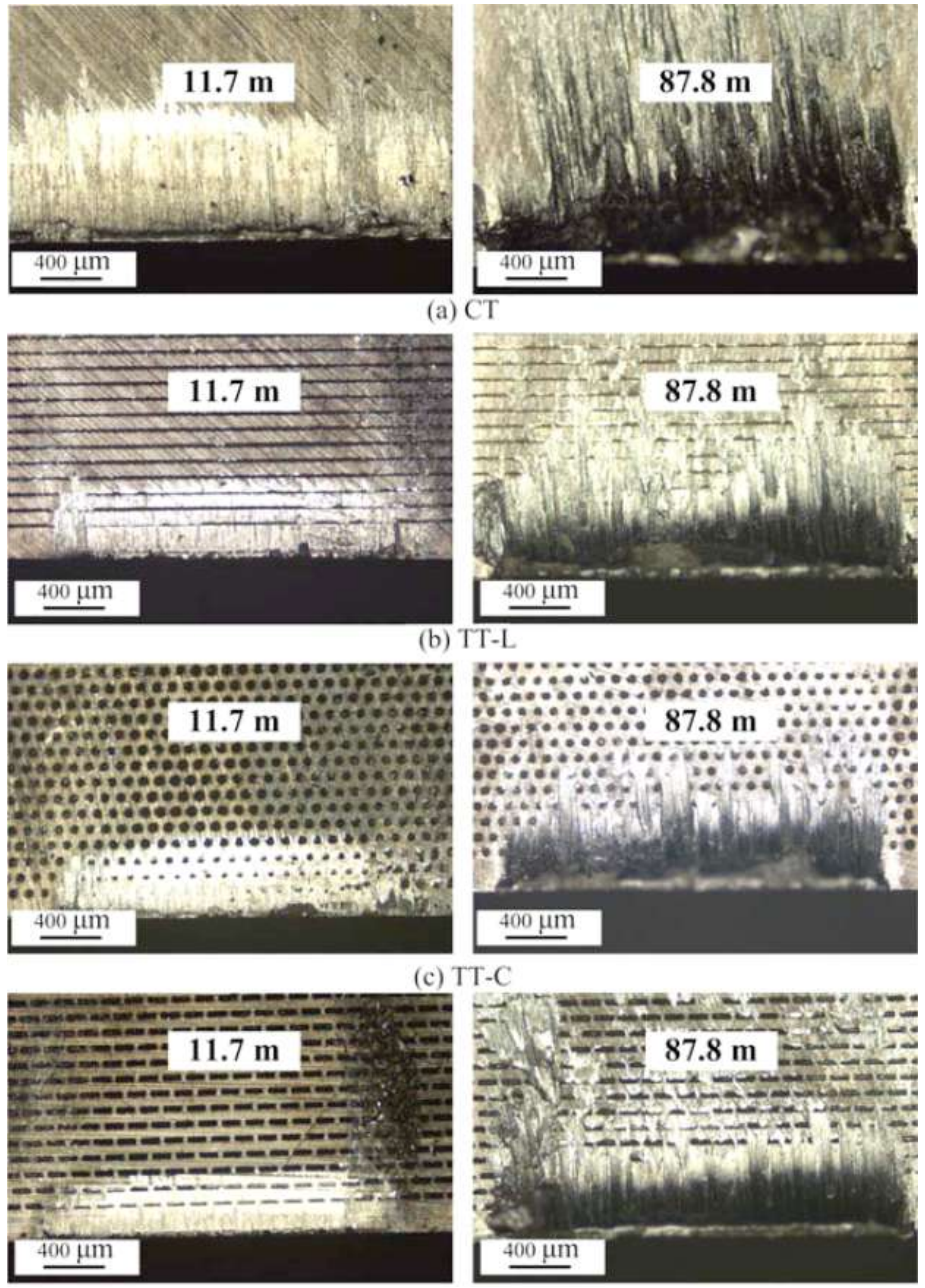
In industrial applications the minimum focus is always > 10 μm, normally 20 μm

Laser texturing as a tool to improve surface characteristics

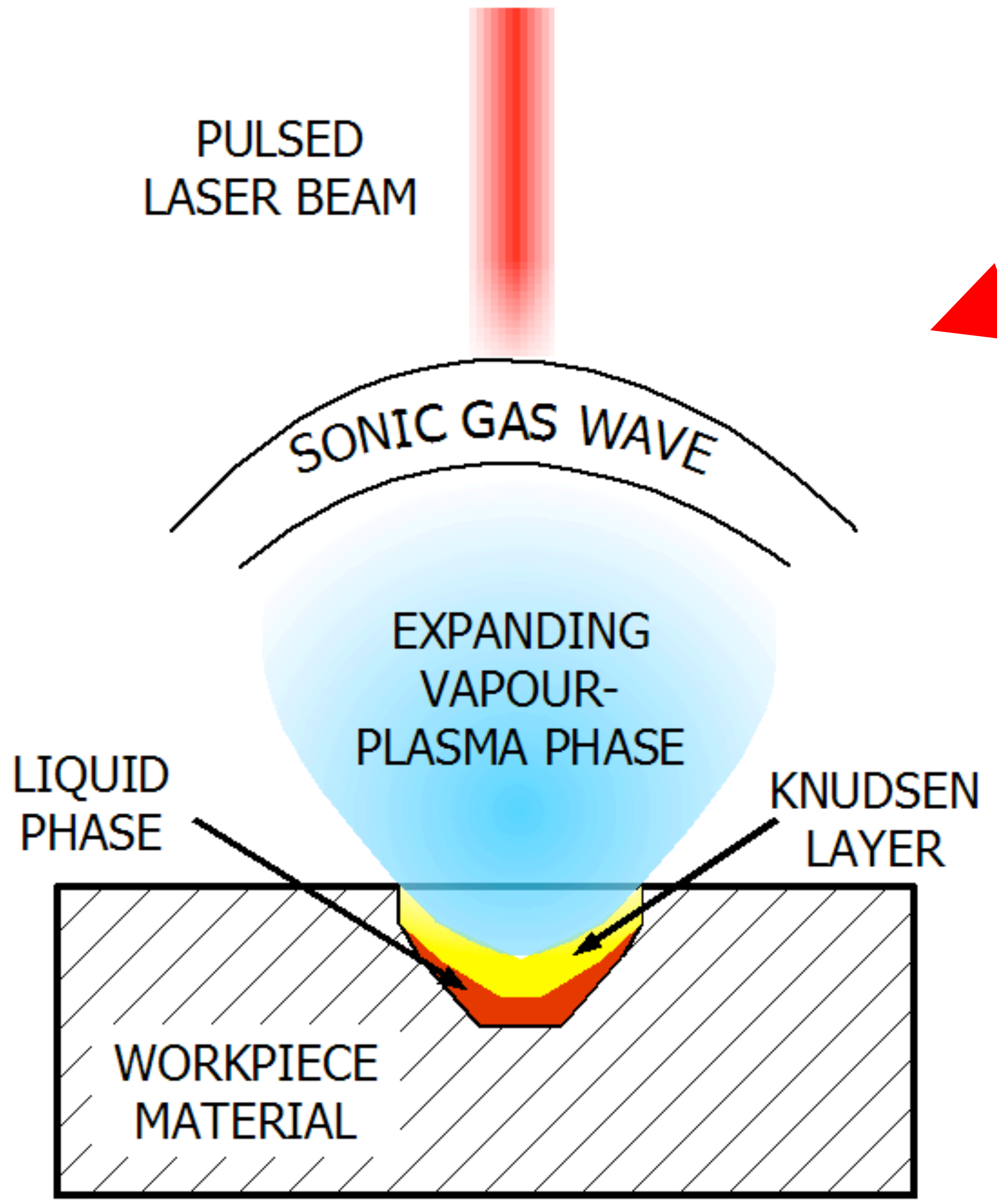
- Wear
- Wettability
- Tribology
- Biomedical
- Photovoltaic
- Microfluidics

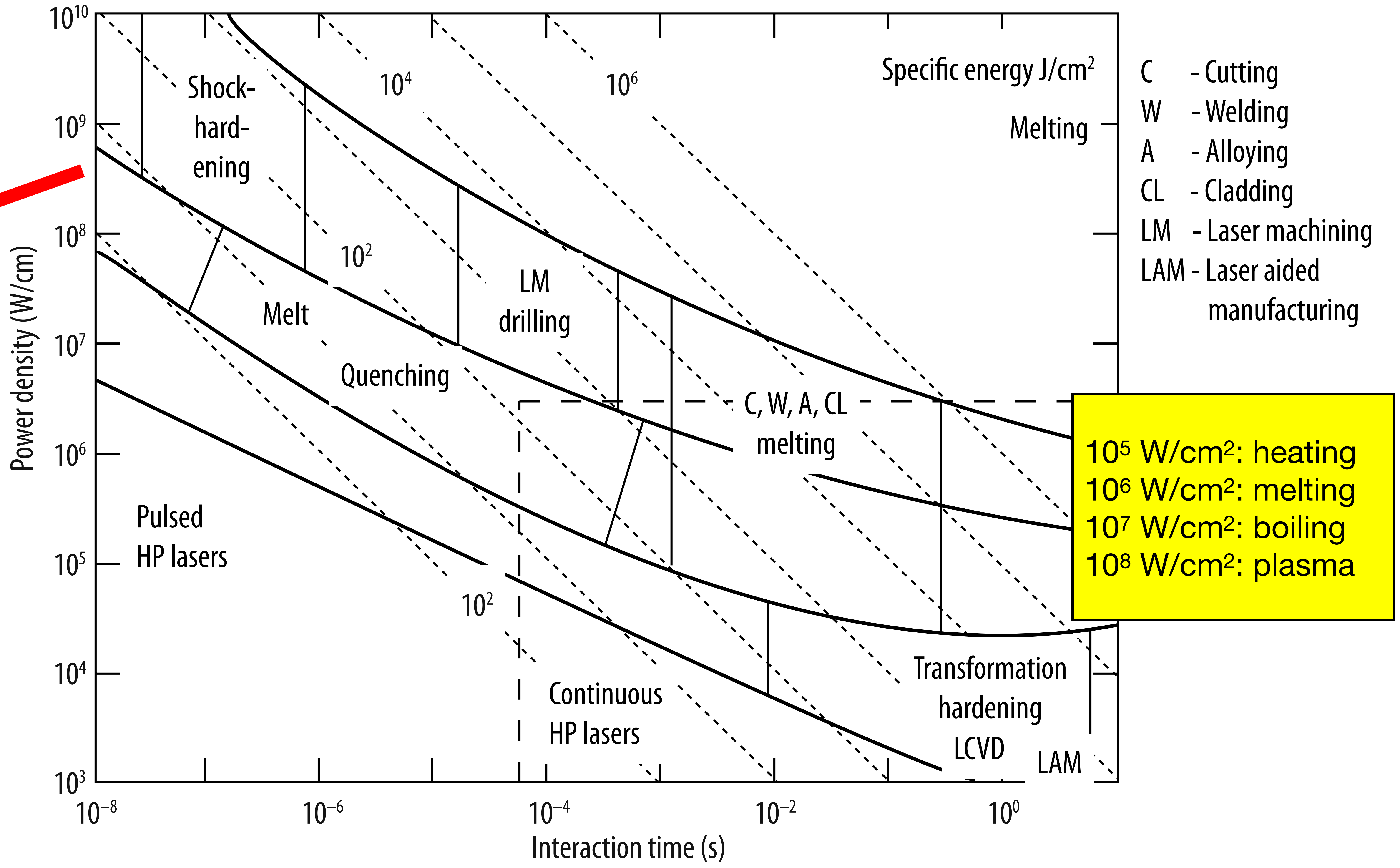






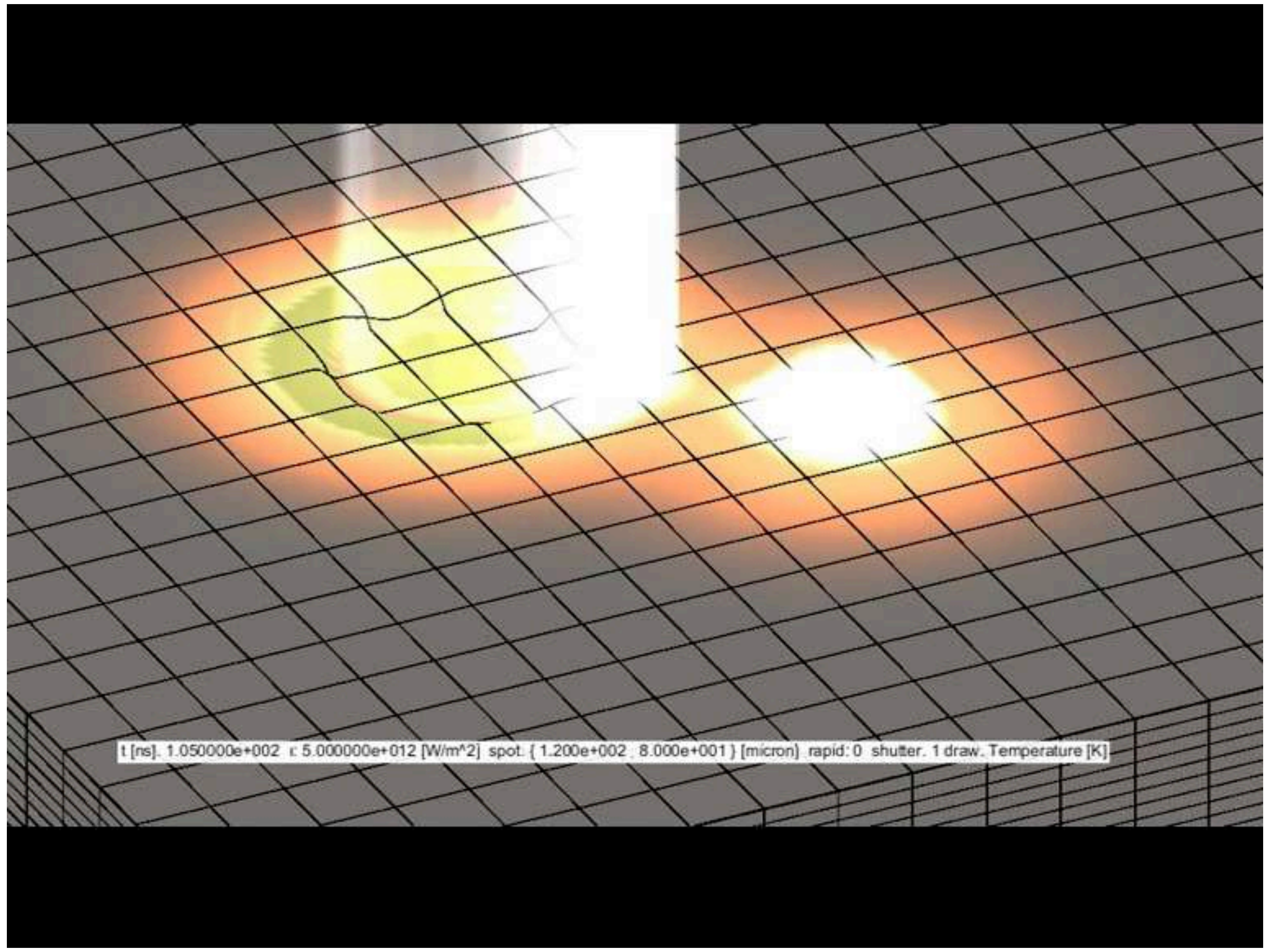
Laser processing, power density and pulse duration



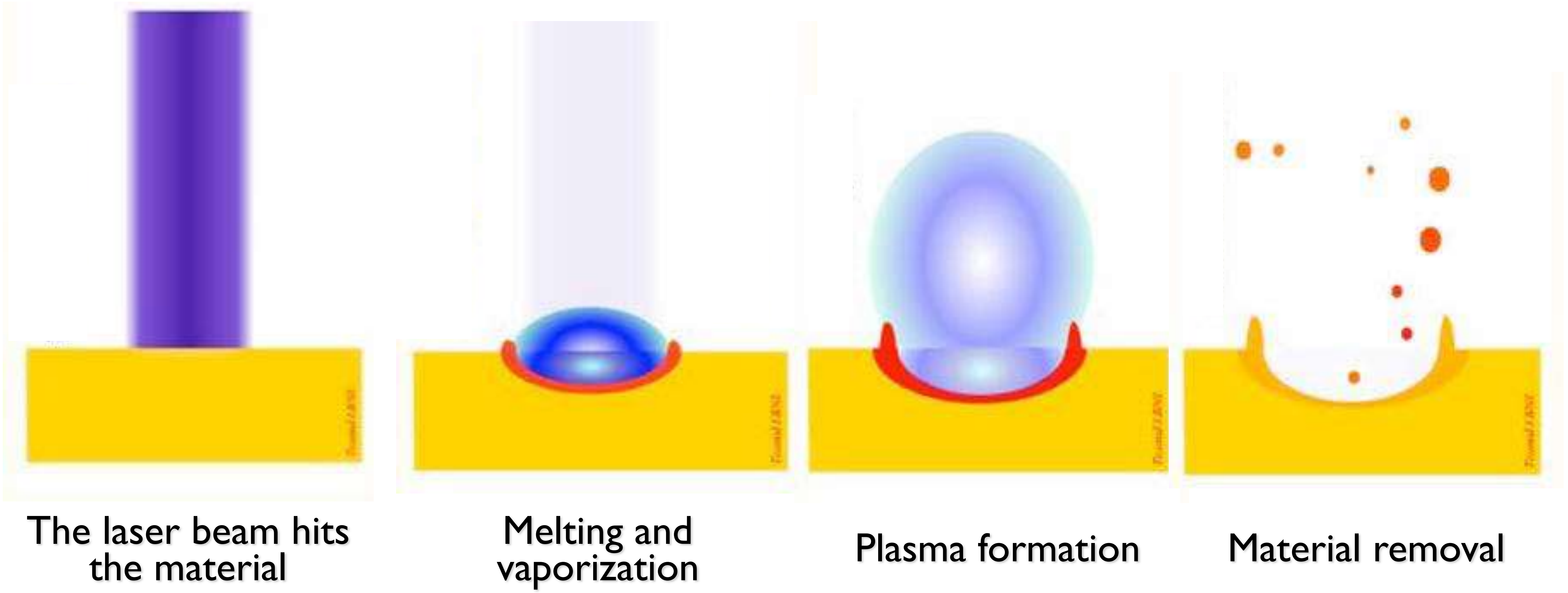


10^5 W/cm^2: heating
10^6 W/cm^2: melting
10^7 W/cm^2: boiling
10^8 W/cm^2: plasma

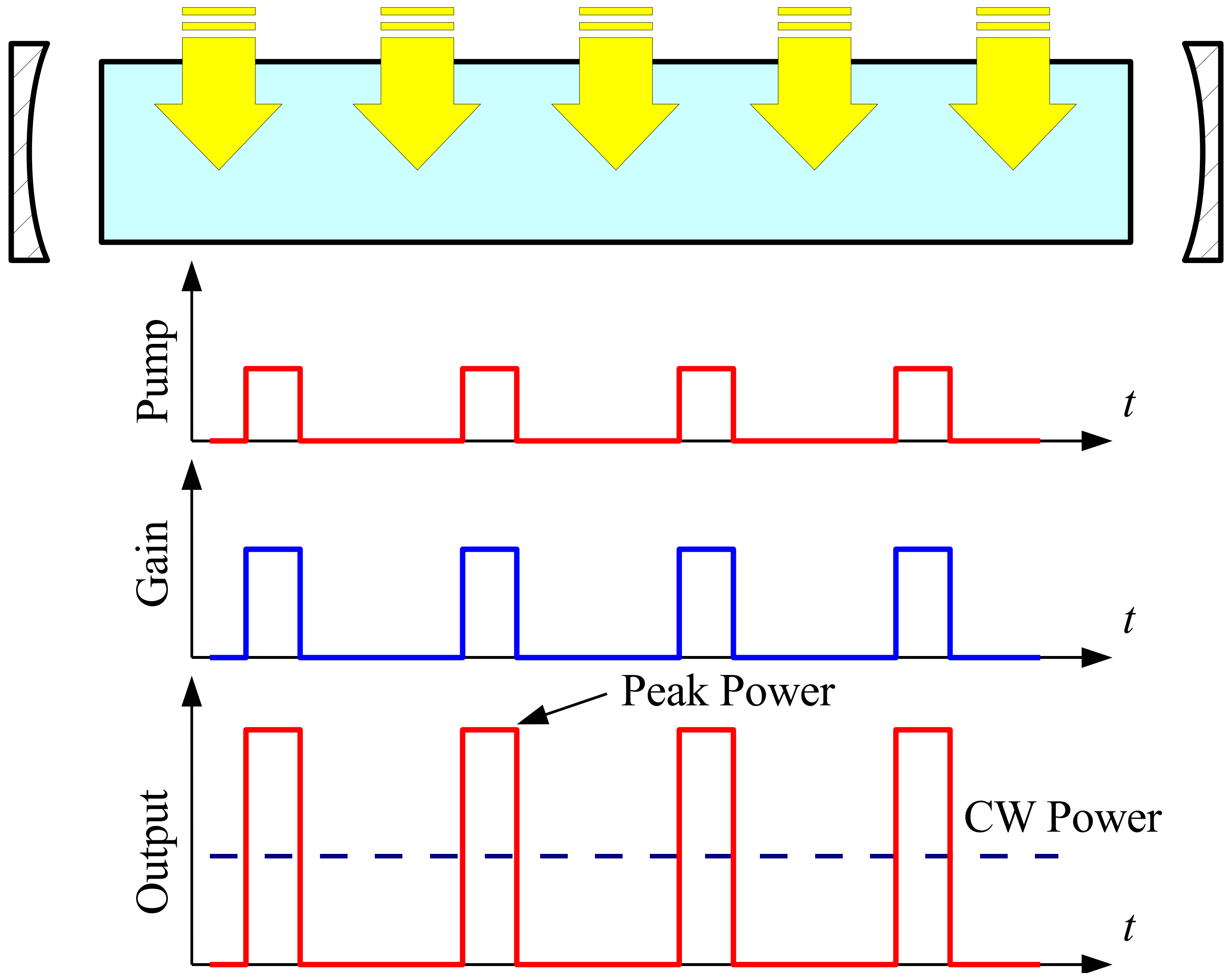
Laser texturing by material ablation

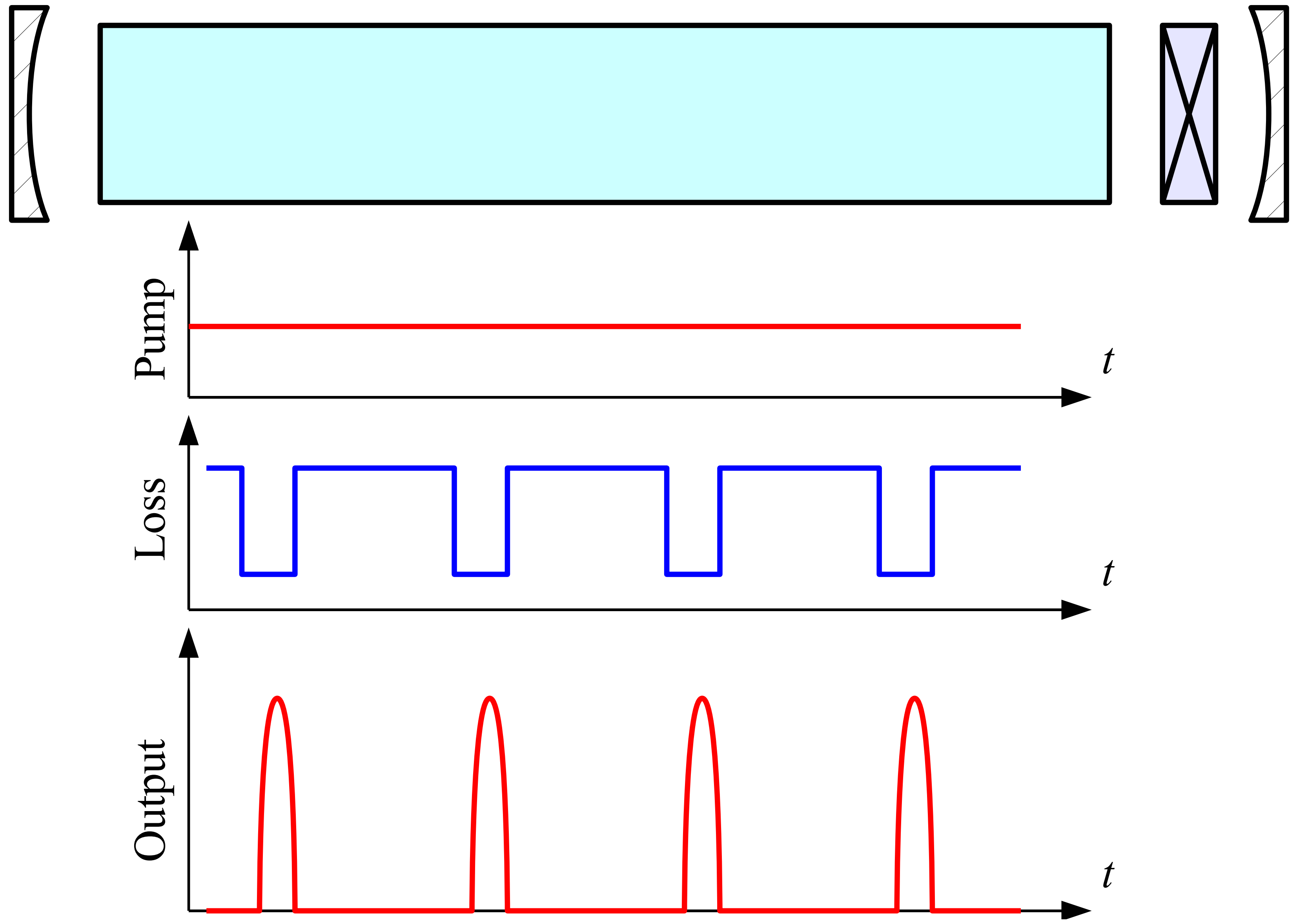


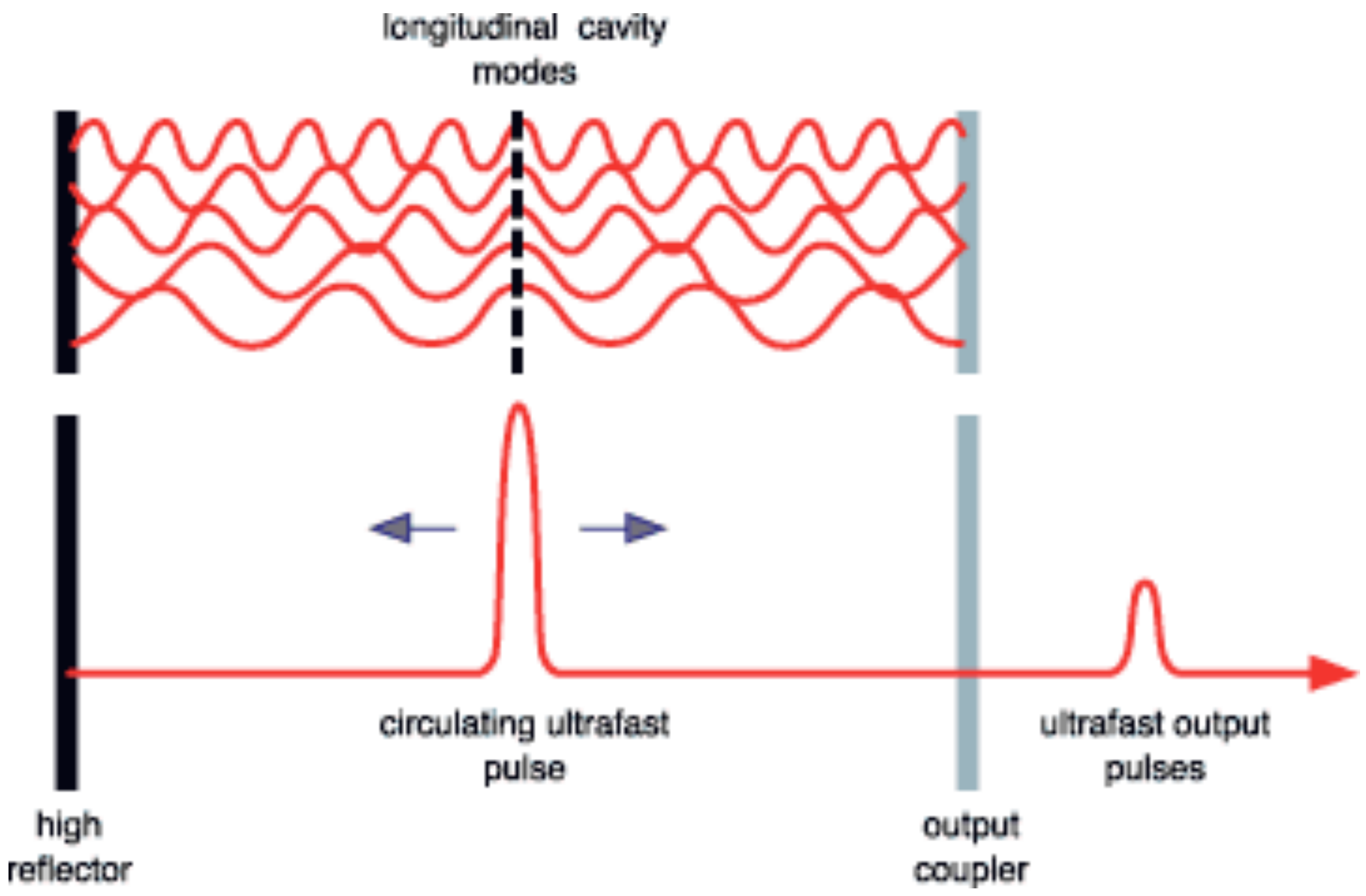
Orazi et. al LASE 2007



LASER: time distribution







Modulation of pumping energy
repetition rate f < 10 kZ
Pulse duration: ms / µs
Peak Power: kW

Q-switching: modulation of reflectivity.
repetition rate f kHz - MHz
Pulse duration: ns
Peak Power: MW

Mode Locking
repetition rate f MHz
Pulse duration: fs/ps
Peak Power: GW (TW/PW)

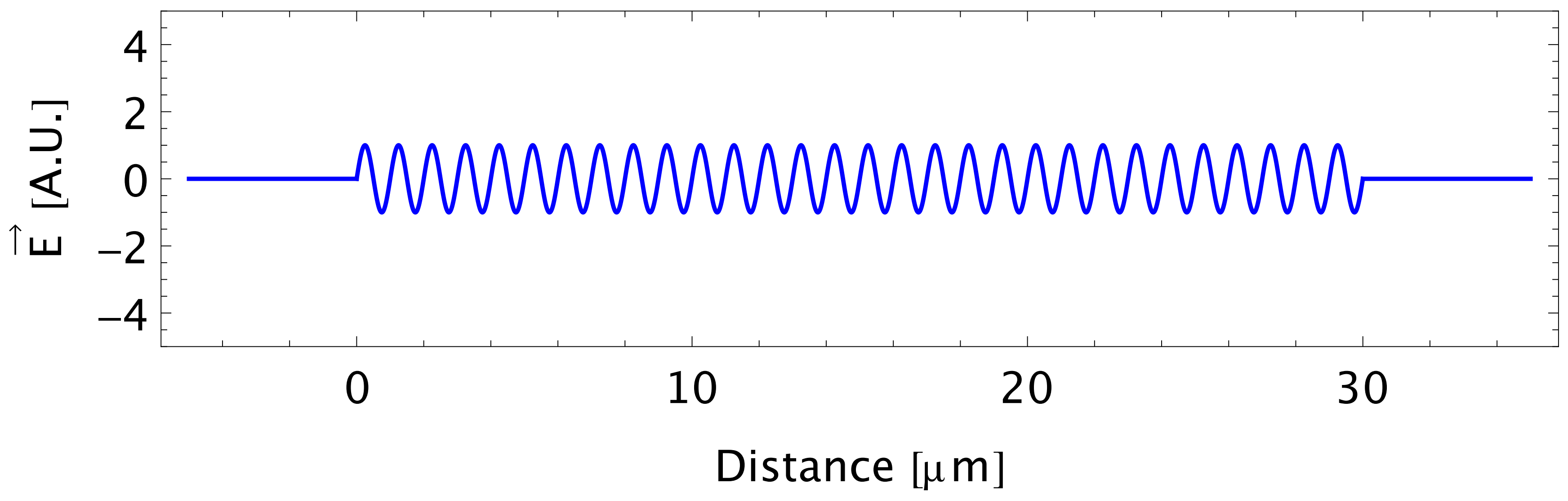
Ultrashort laser sources: extreme peak power

$$\lambda = 1030\ nm$$

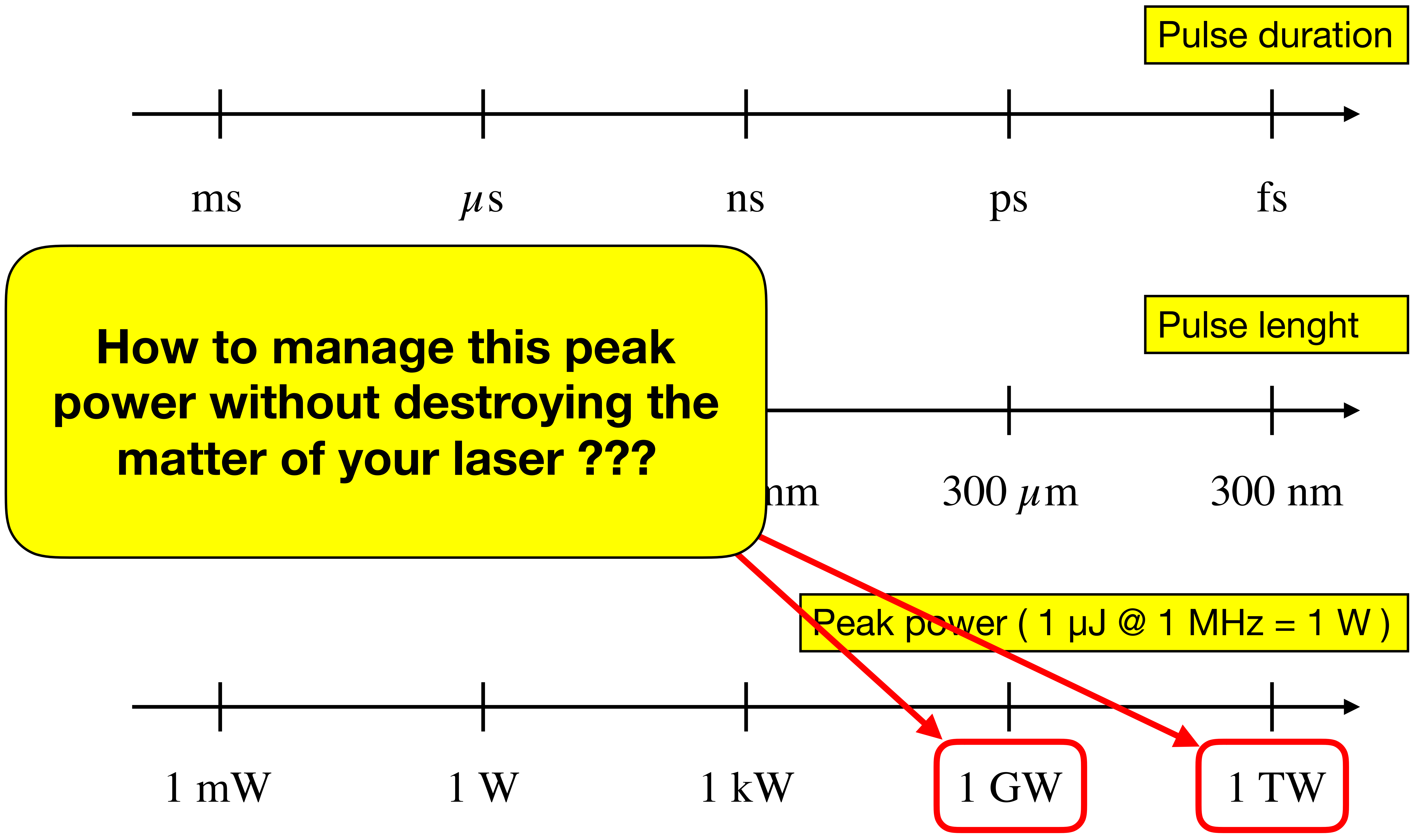
$$\tau_p = 100\ fs = 1 \cdot 10^{-13}\ s$$

$$c \approx 3 \cdot 10^5 km/s \approx 3 \cdot 10^9\ mm/s$$

$$l_p \approx 30\ \mu m$$

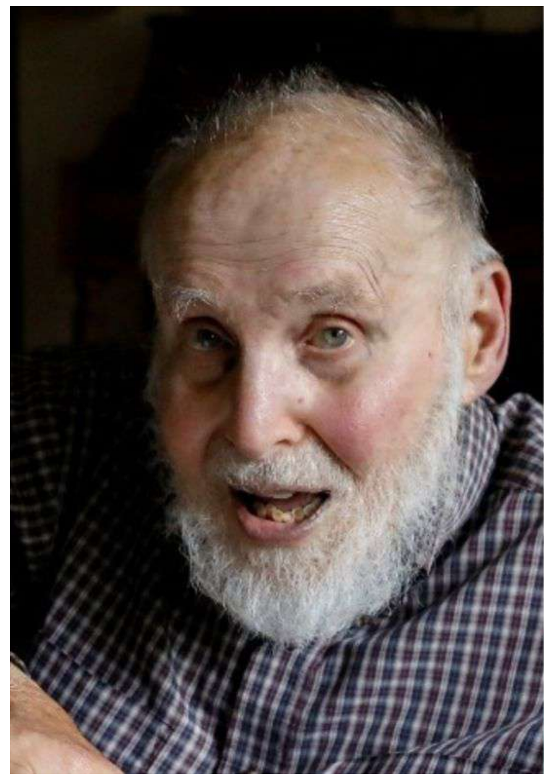


Only 30 oscillations of the electric field…

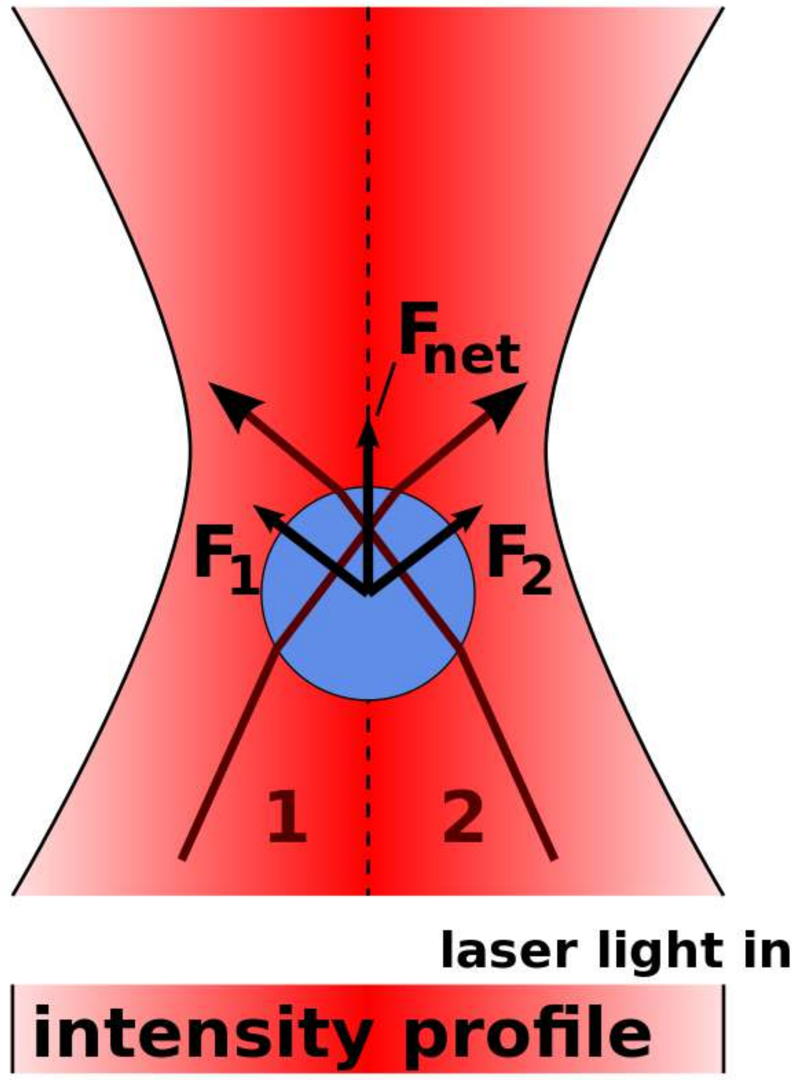


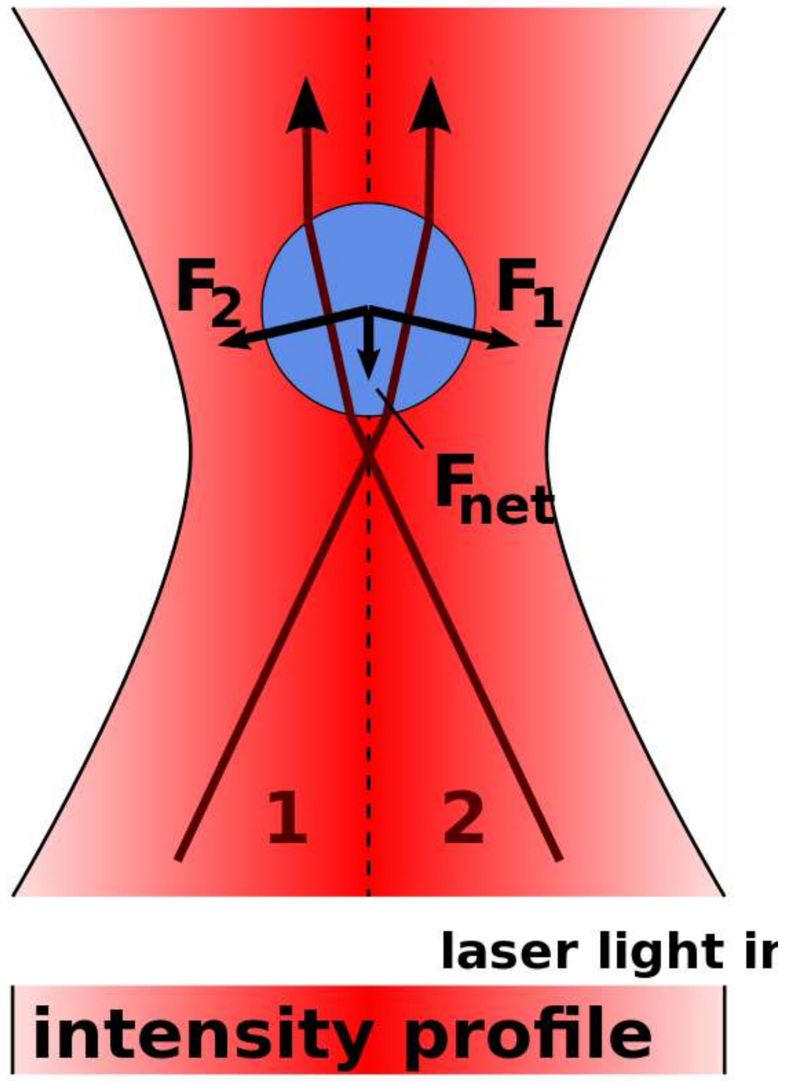
Nobel prize in Physics 2018…

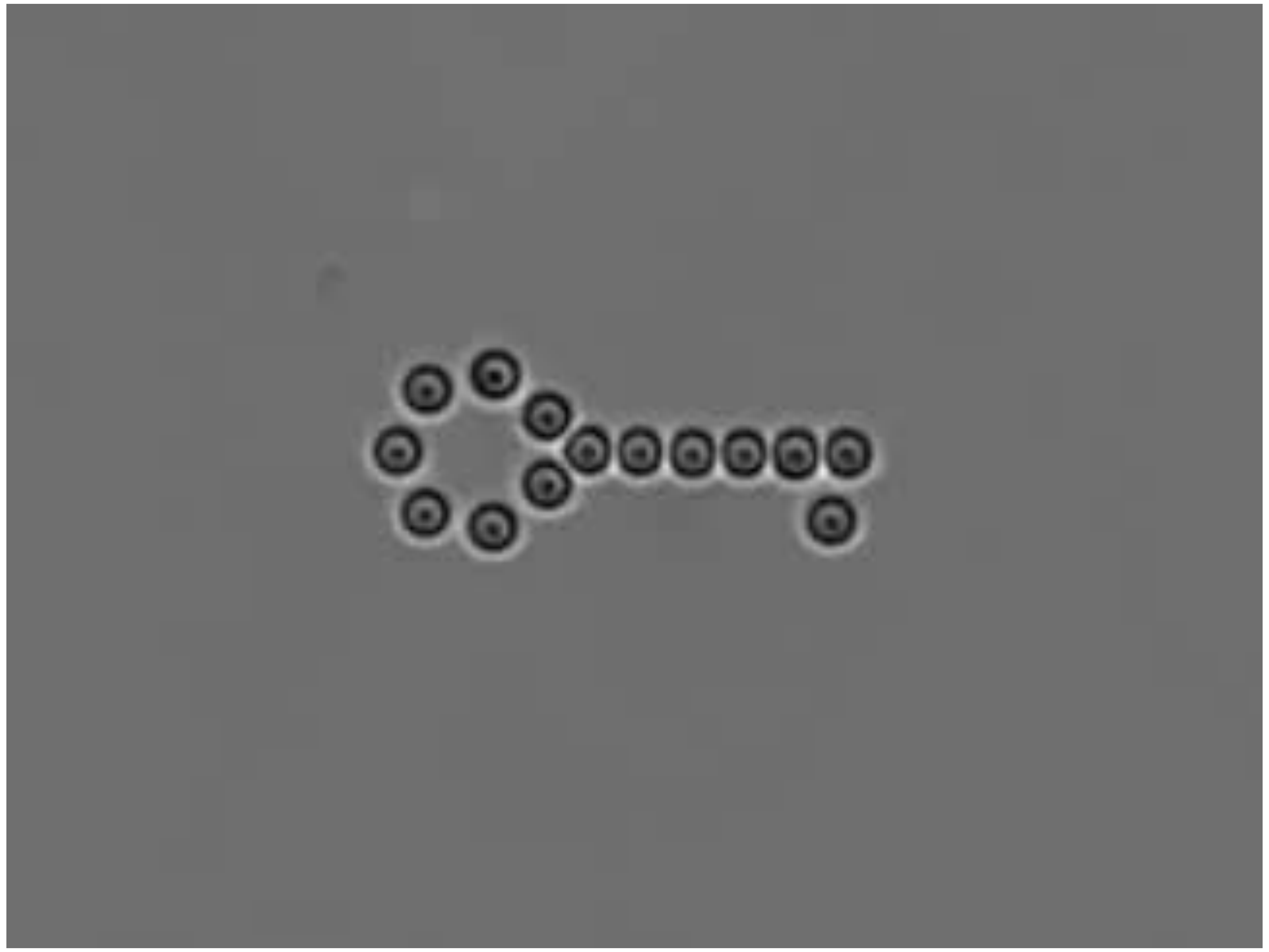
Nobel prize in Physics 2018...



Arthur Ashkin (USA)

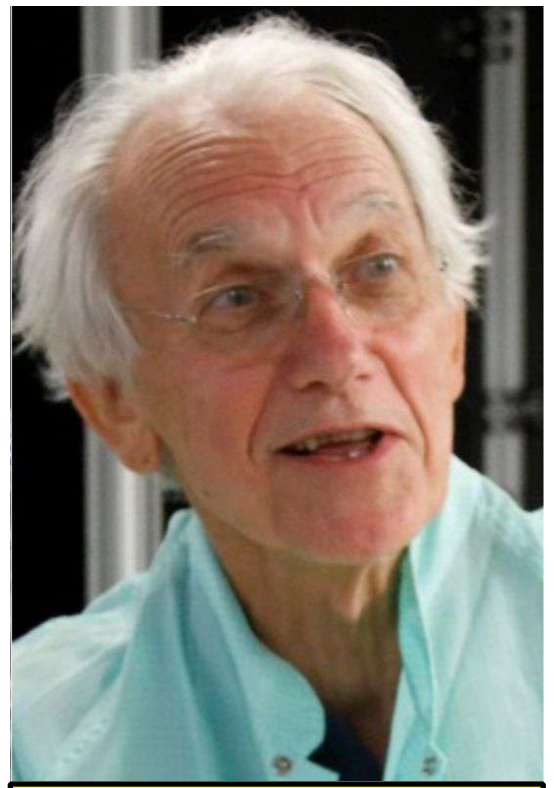






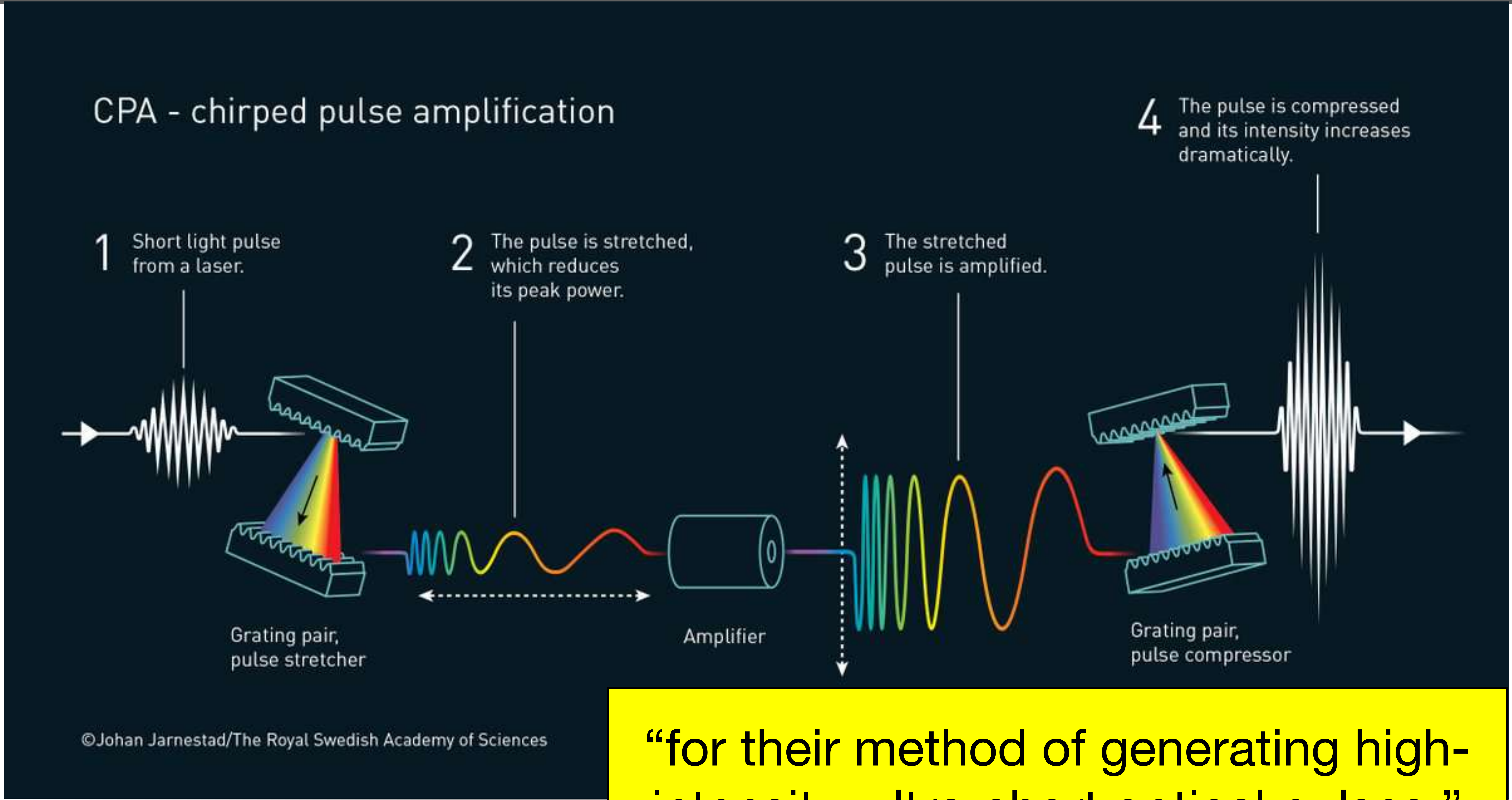
"for the optical tweezers and their application to biological systems"

Nobel prize in Physics 2018…



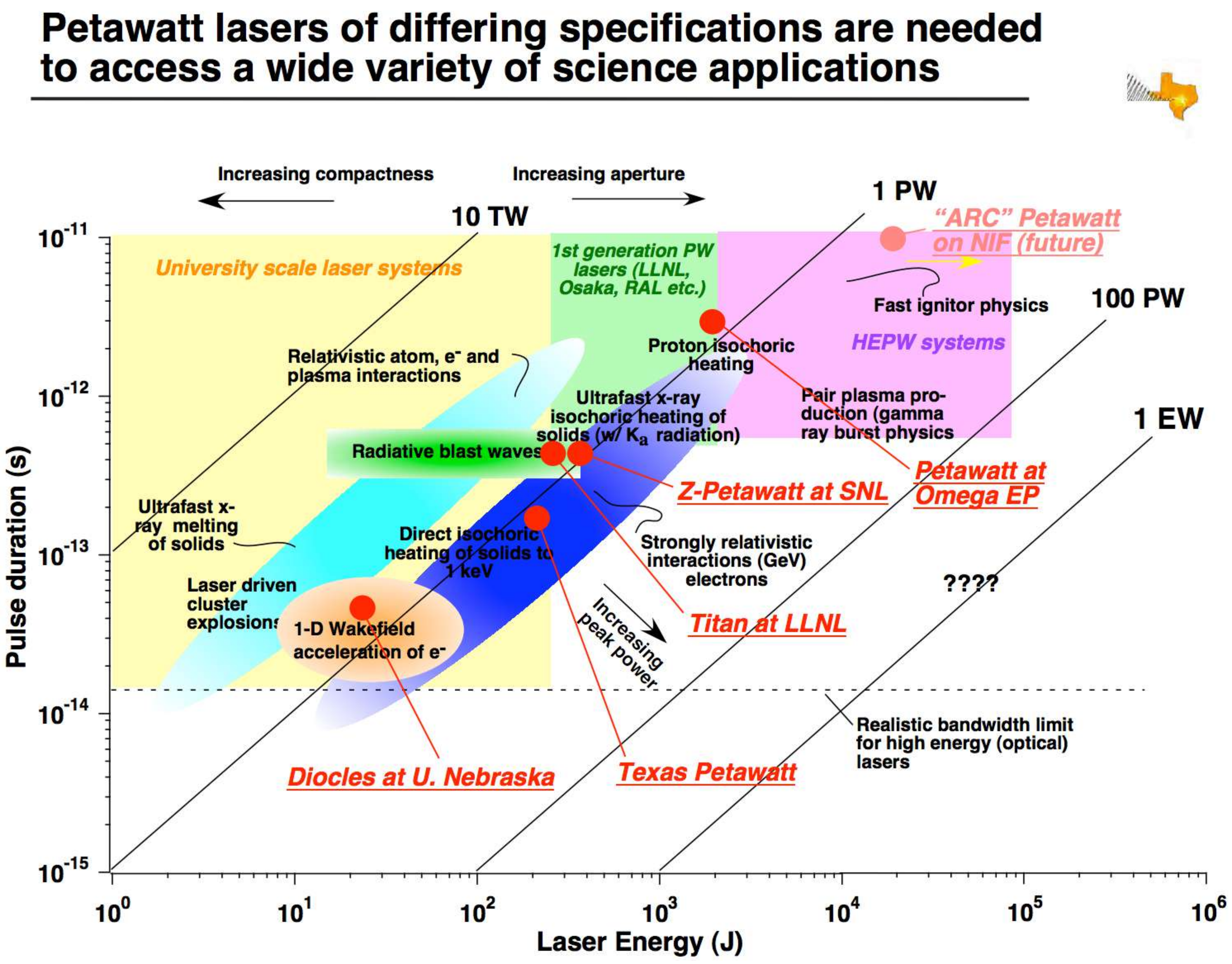
Gerard Mourou (France)

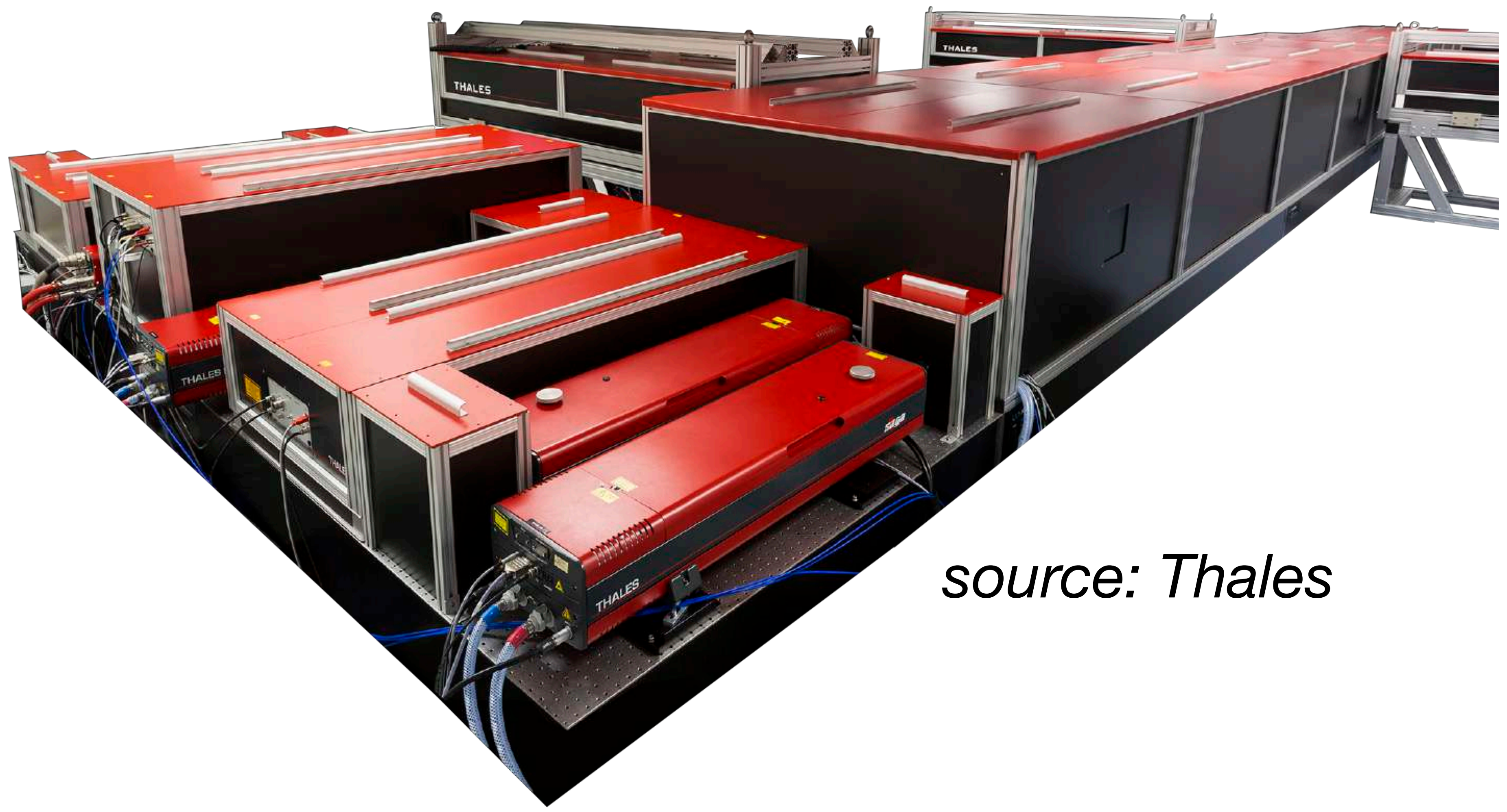
Donna Strickland (Canada)



"for their method of generating high-intensity, ultra-short optical pulses."

Ultrashort lasers advances driven by scientific applications: nuclear fusion & high energy physics





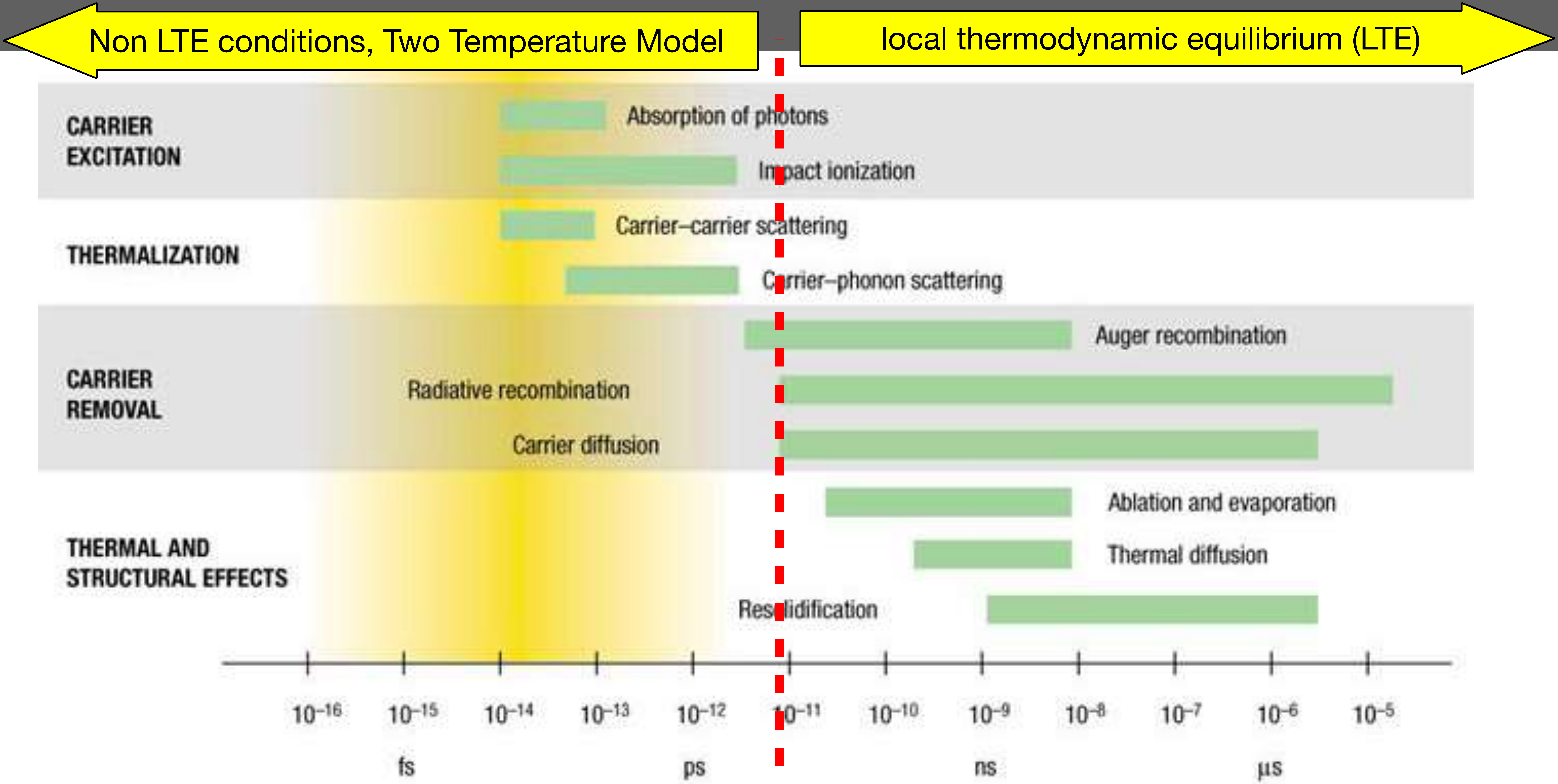
source: Thales

Up to 100 J at 25 fs pulse duration!!!

1.1 (1.9) kW at 710 fs pulse duration

Negel et al. SPIE 9135 (2014)

Ultrashort laser sources: laser matter interaction



Ultrashort lasers: robustness, operability, reliability

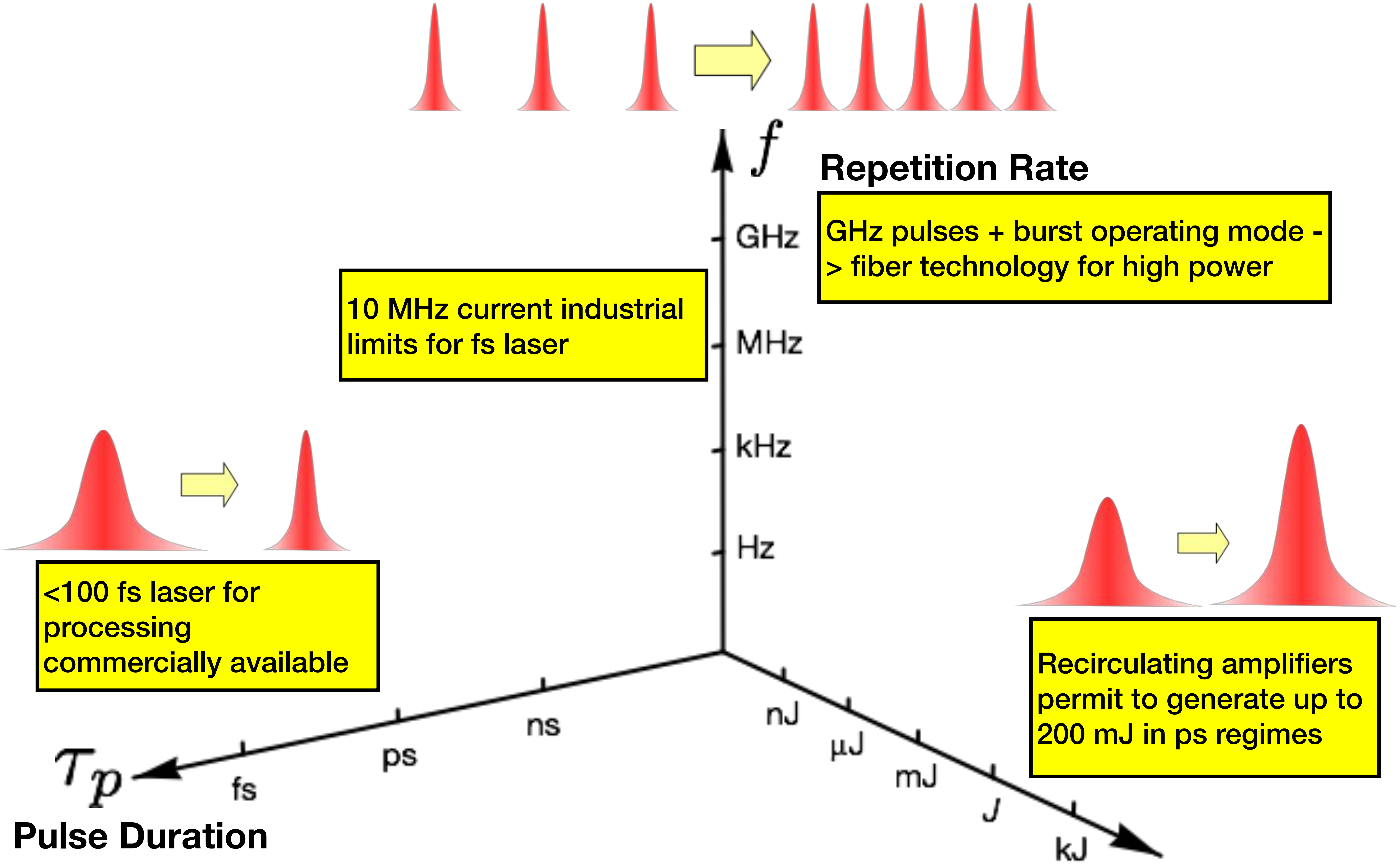
www.amplitude-systemes.com

www.ekspla.com

www.spectra-physics.com

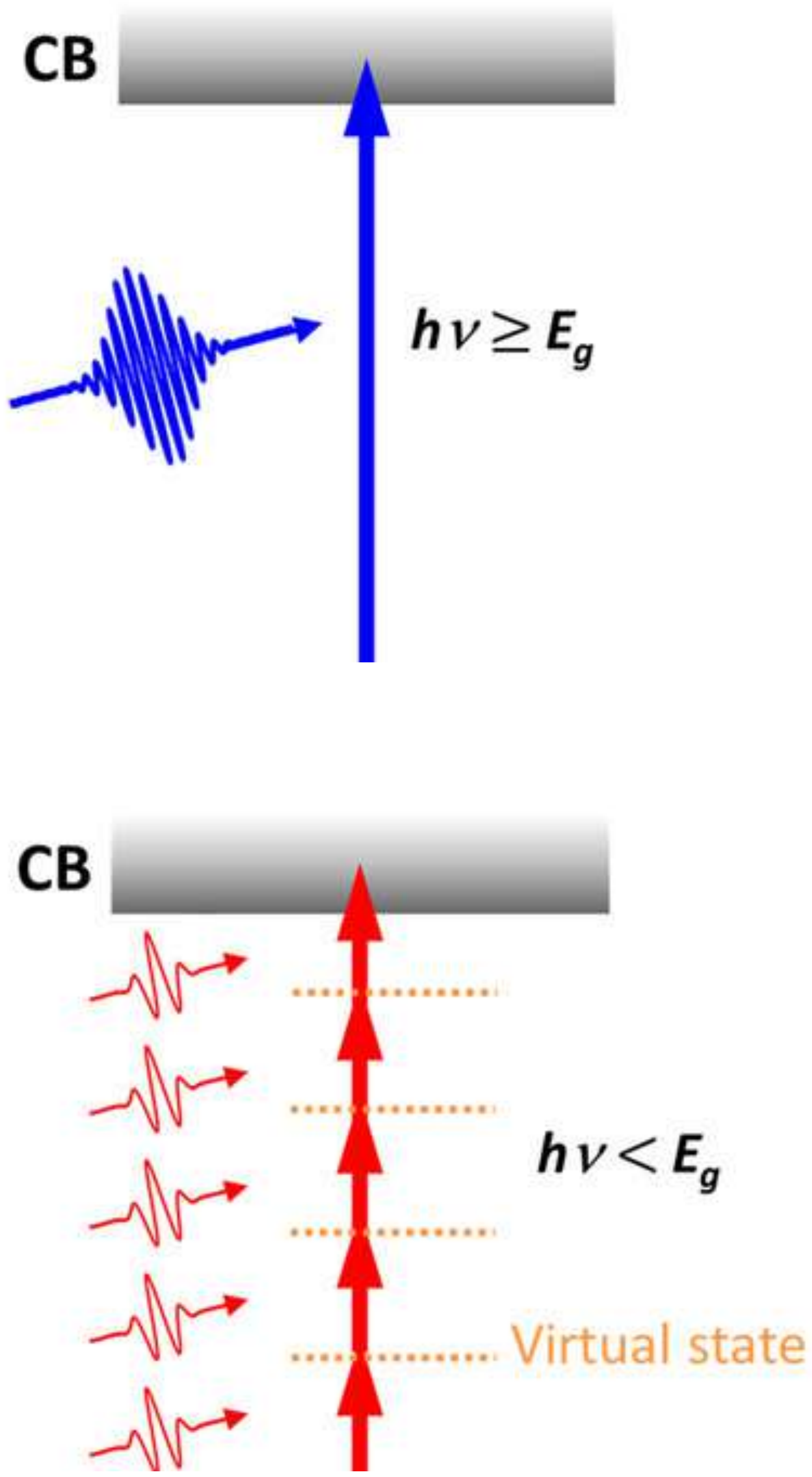
www.lightcon.com

www.coherent.com

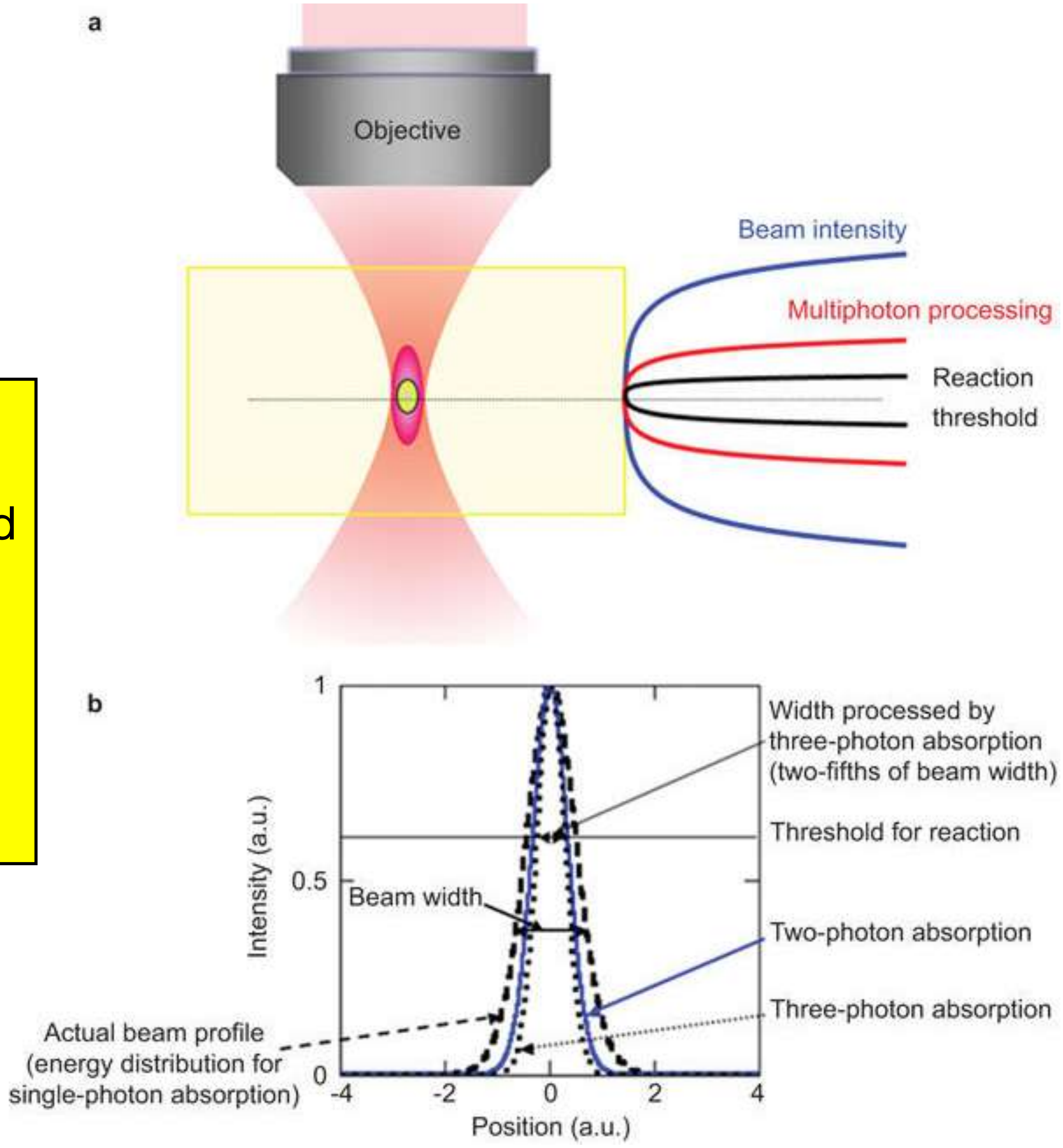


- Ultrashort fiber technology for mid-low power range opened to the industrial use of robust and reliable sources

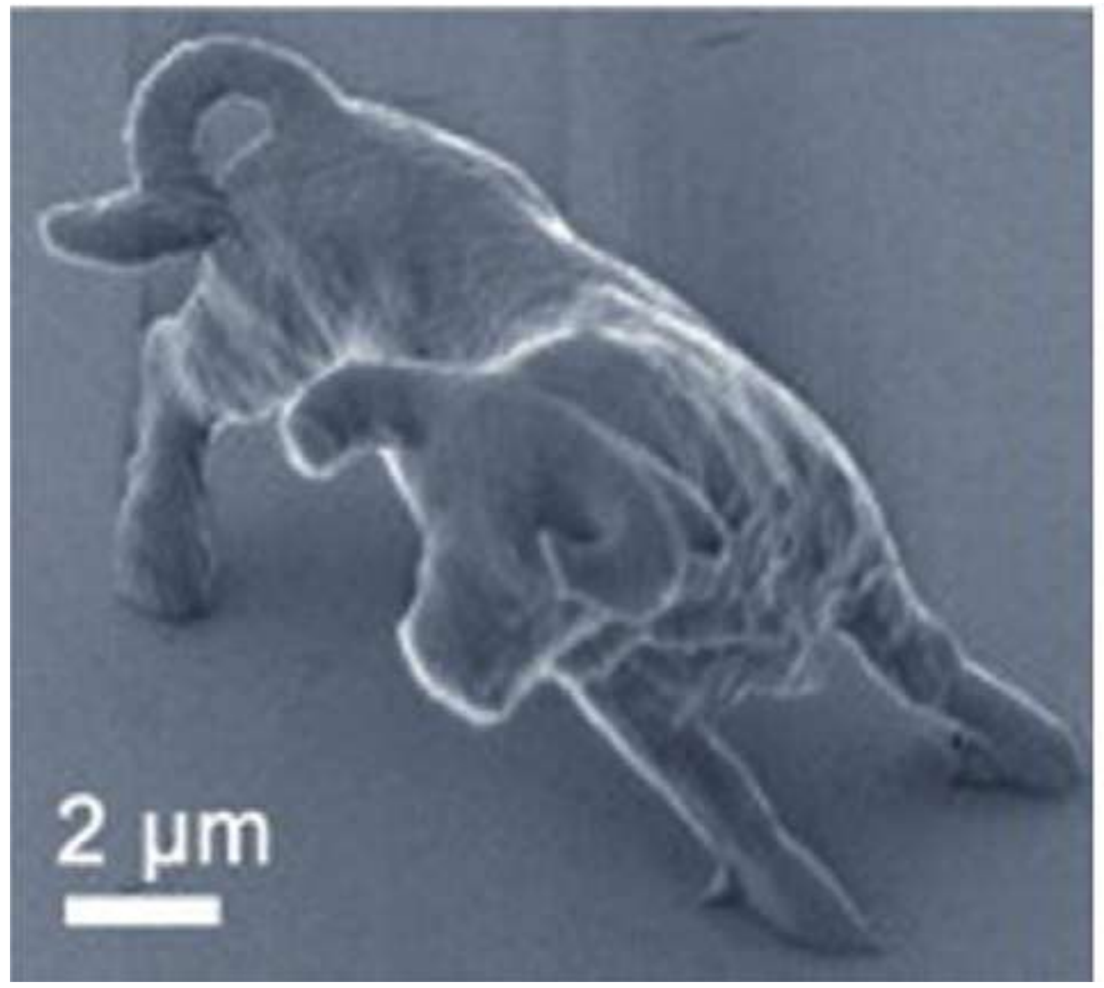
Exotic processes: multiphoton processing and cold ablation



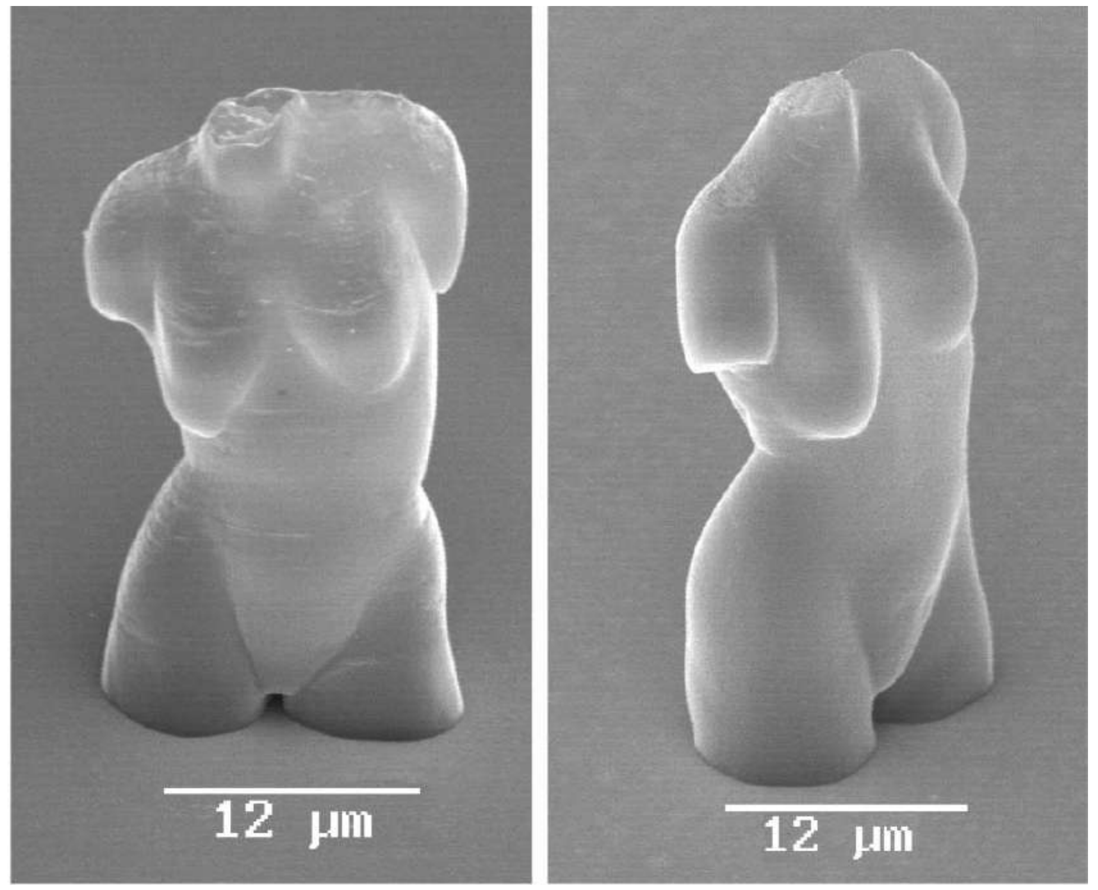
Multiphoton absorpion and reaction threshold permits to **overcome the diffraction limit**



Sugioka & Cheng Light: Science & Applications 3, (2014)



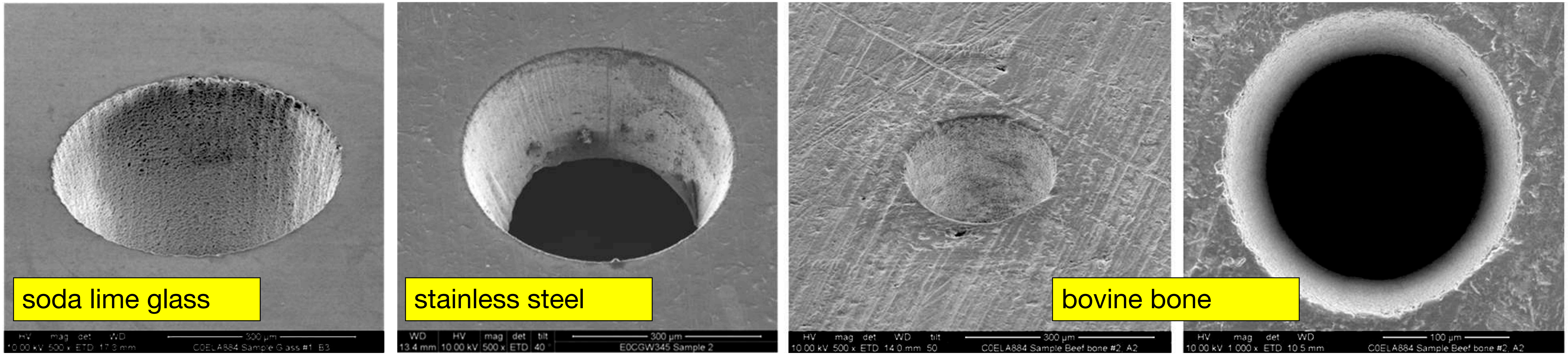
Kawata et al - Nature (2001)



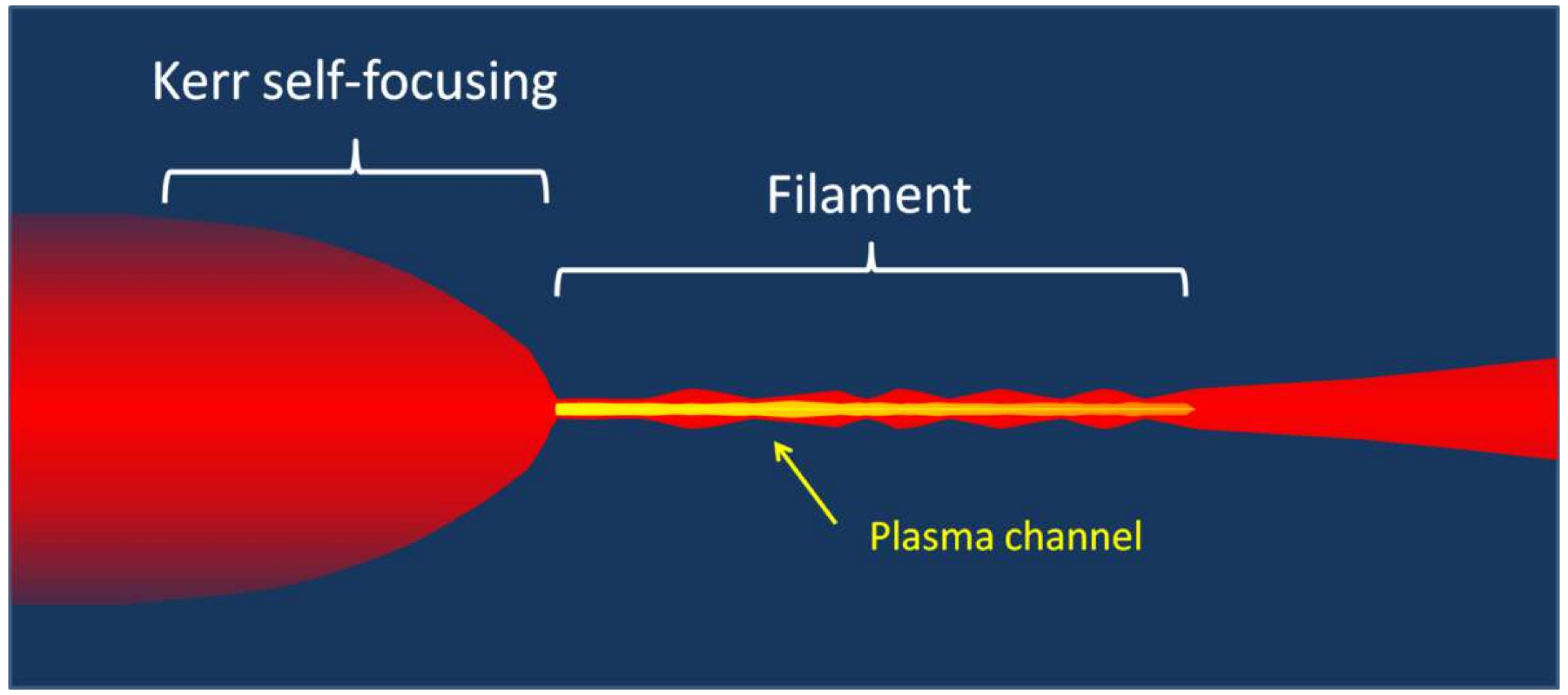
Serbin, J et al. Opt Letters (2003)

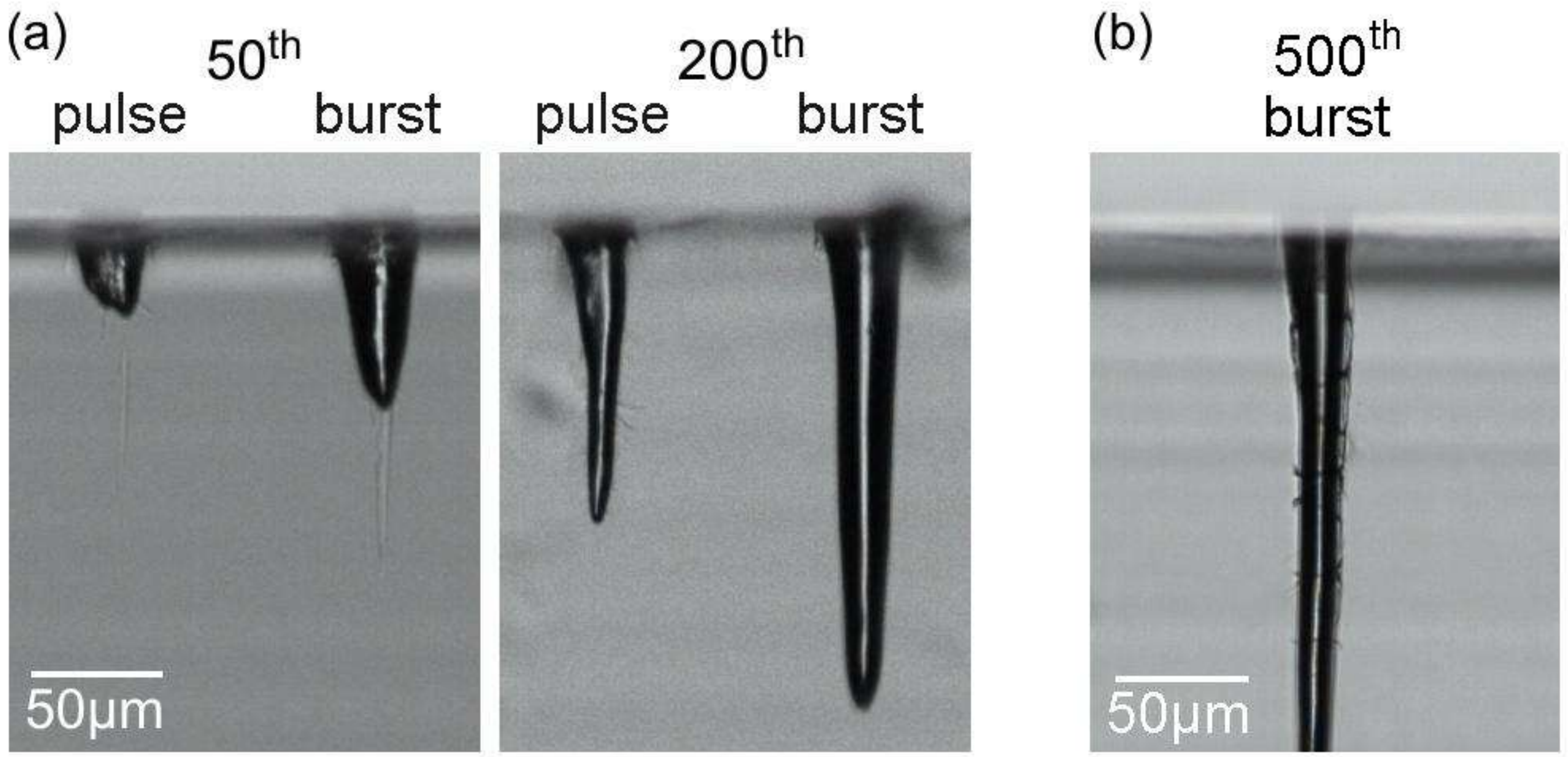
Exotic processes: multiphoton processing and “cold” ablation

Huang, Yang Liu, Opt. Eng. (2014)

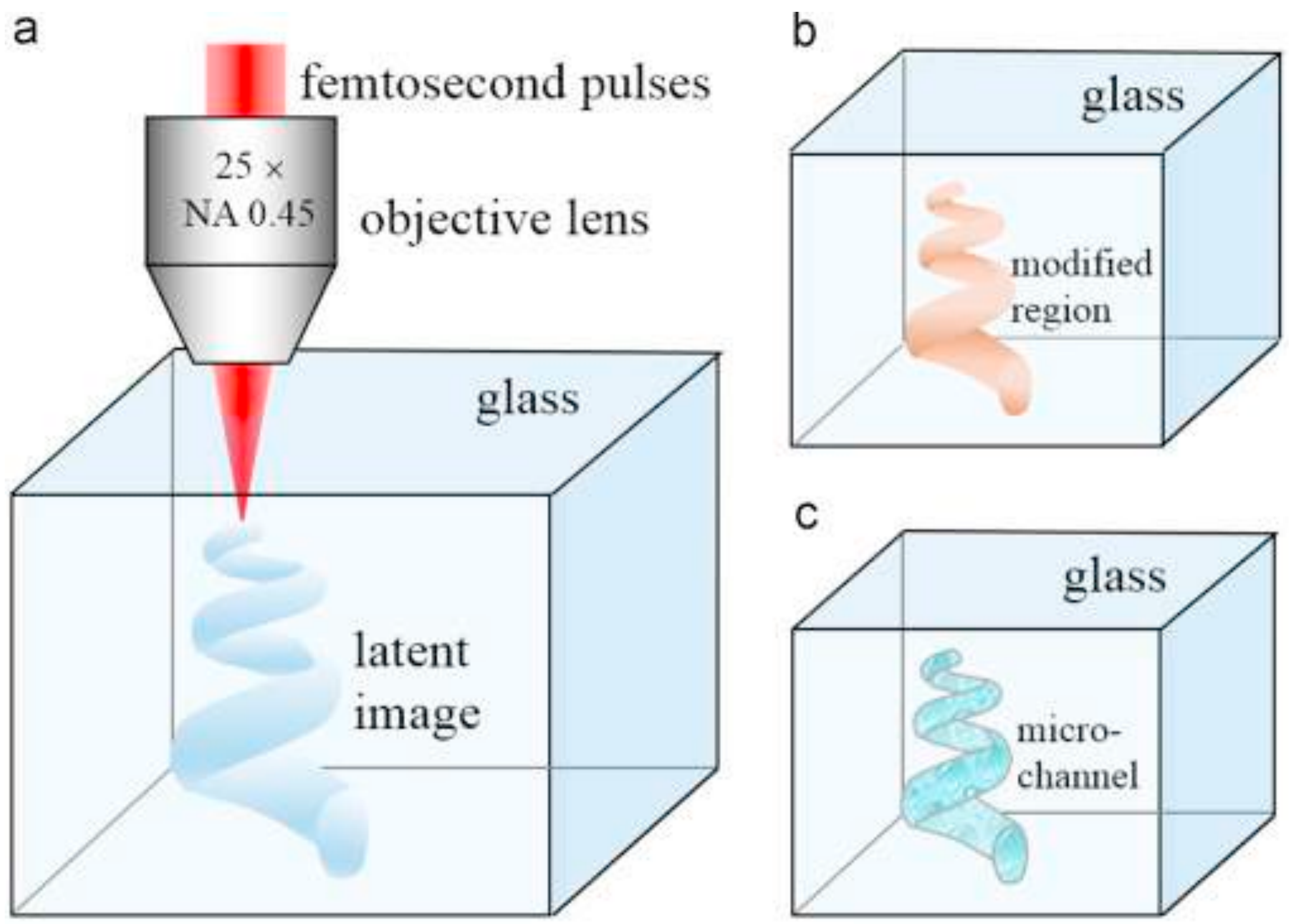


Exotic processes: filamenting and bulk processing

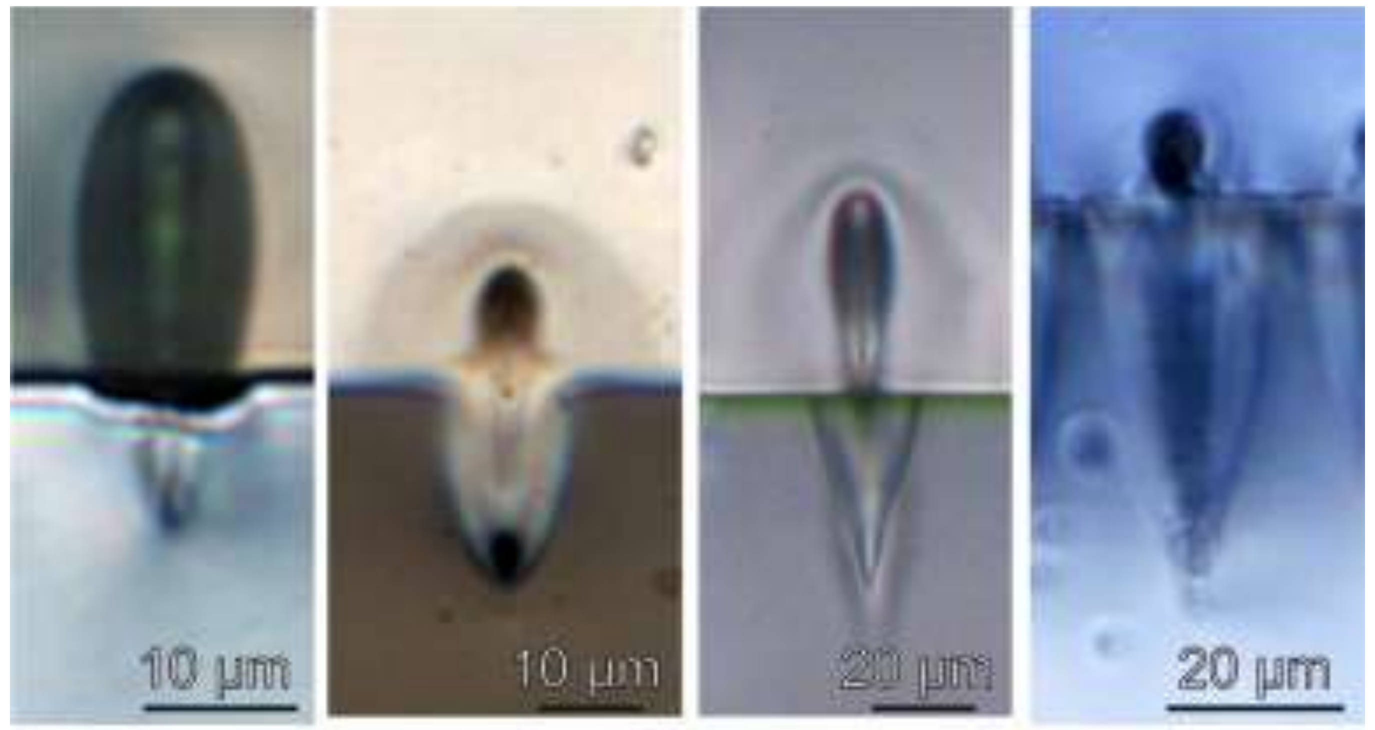




D. Esser et al. Optics Express 2011

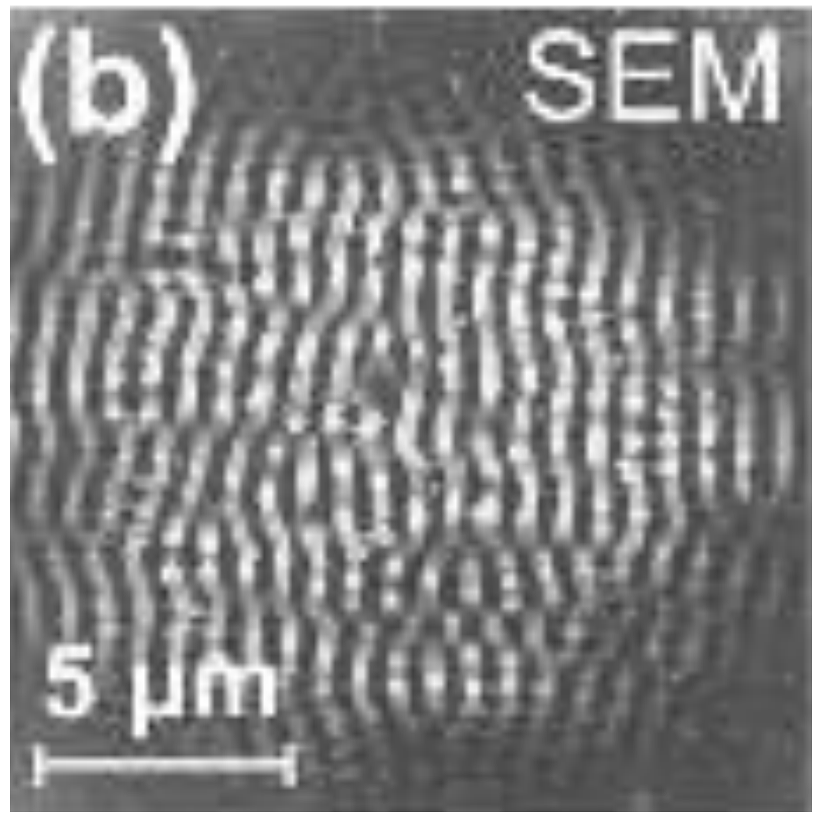


Watanabe et al - Opt & Laser Tech 78A 2016

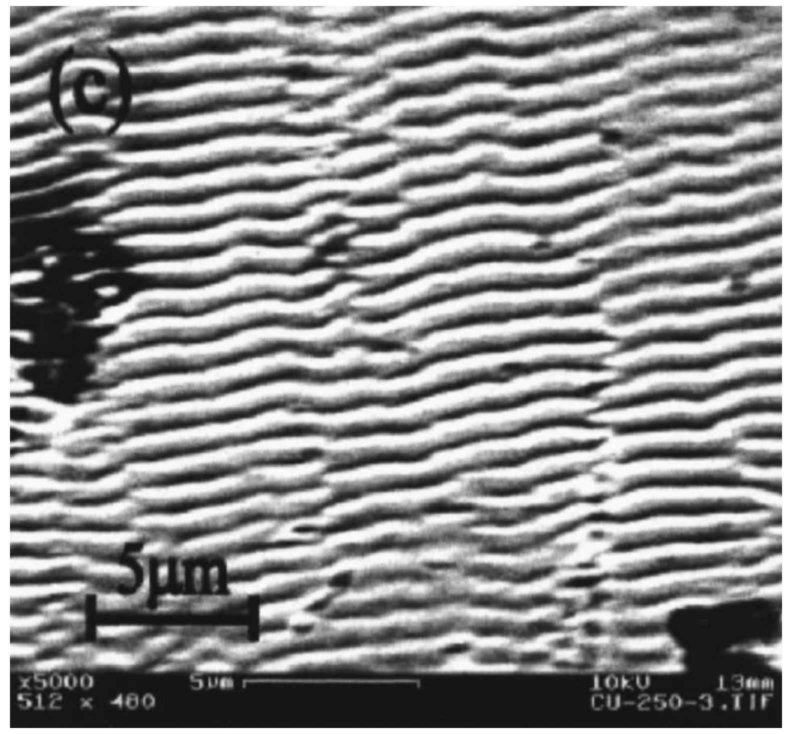


Richter et al. Opt & Laser 83 2016

Exotic phenomena: Laser Induced Periodic Surface Structures

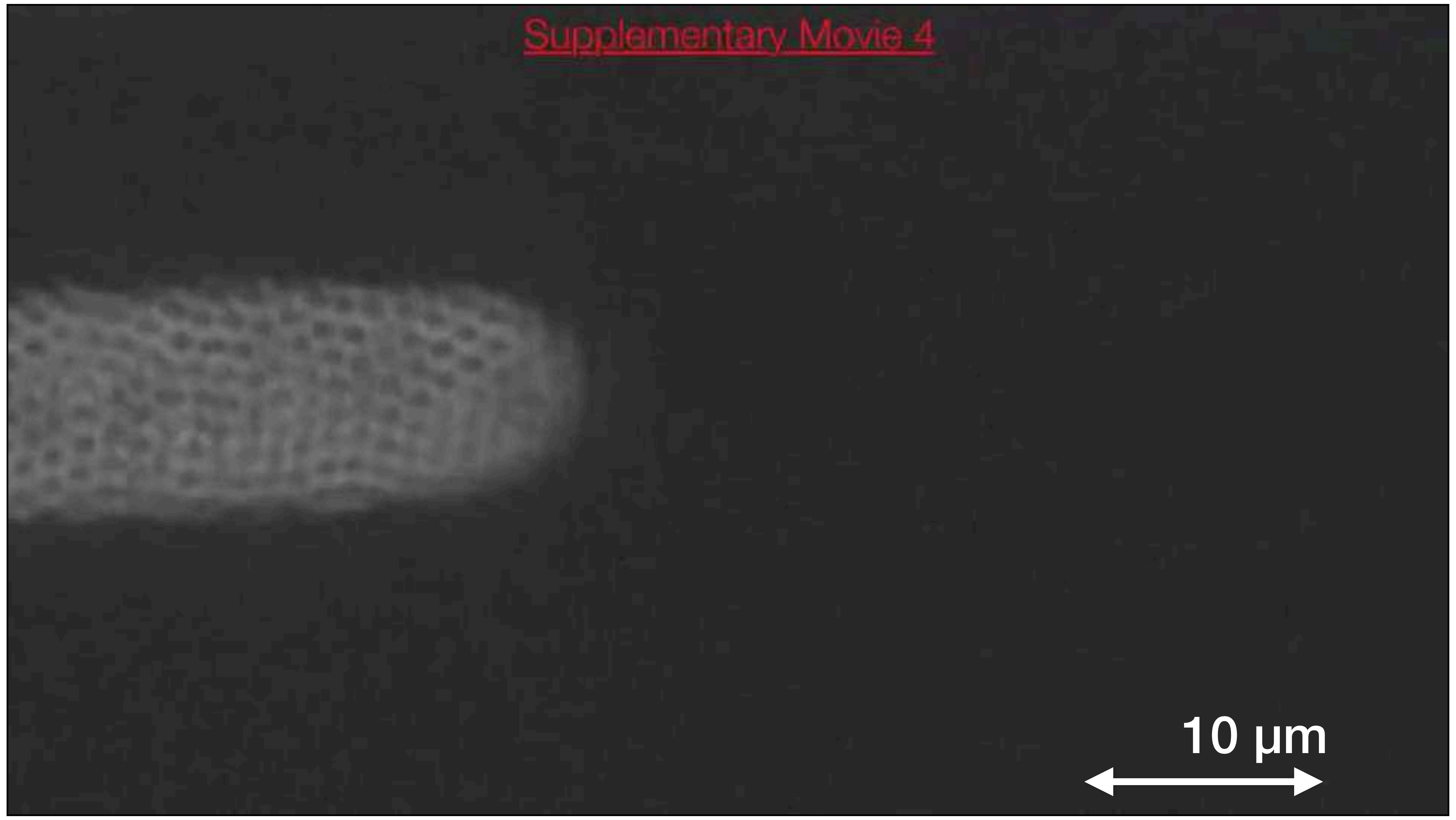


Young et al. 1982



Guo et al, 2005

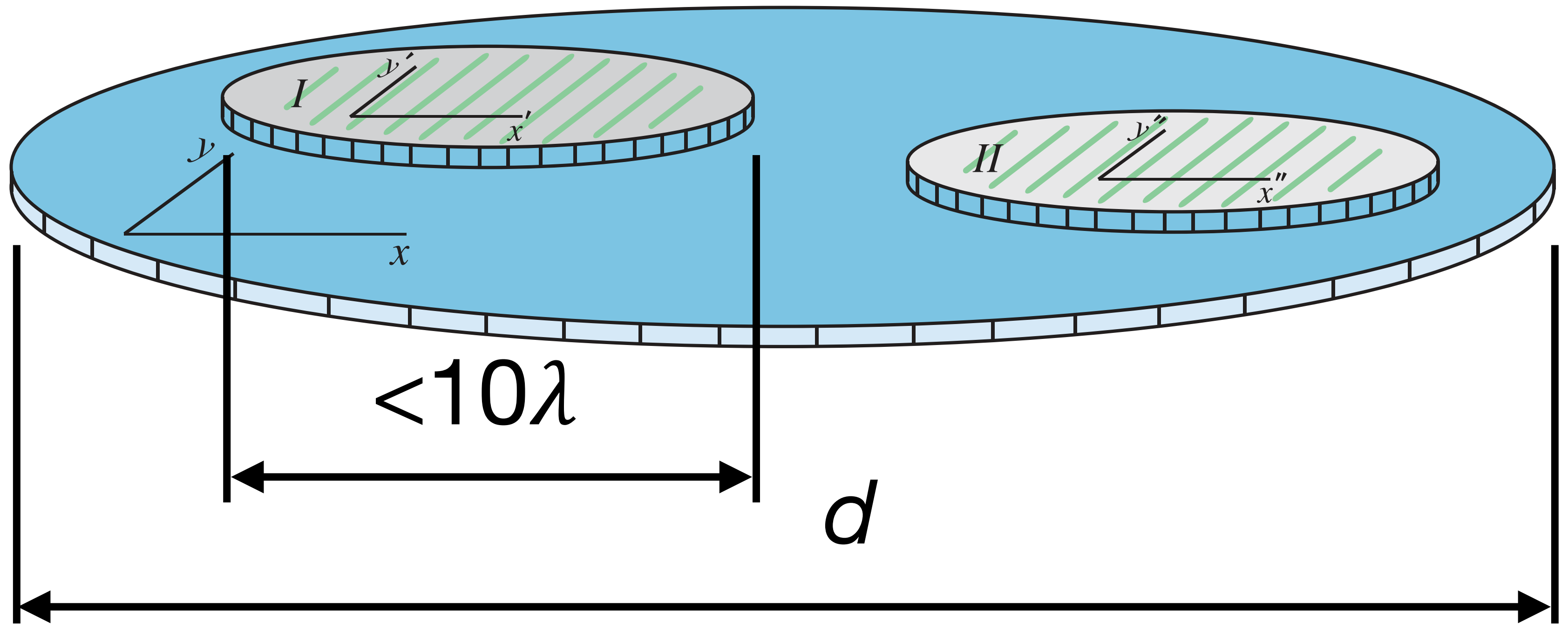
- First observed in dielectric in 1965
- Underlining physics not clear
- Electro dynamics model (Surface Plasmon Polaritons interaction)
- Interference models
- High non linear phenomena (changes in electromagnetic/ optical material constants)
- Effects amplified when using ultrashort laser pulses.

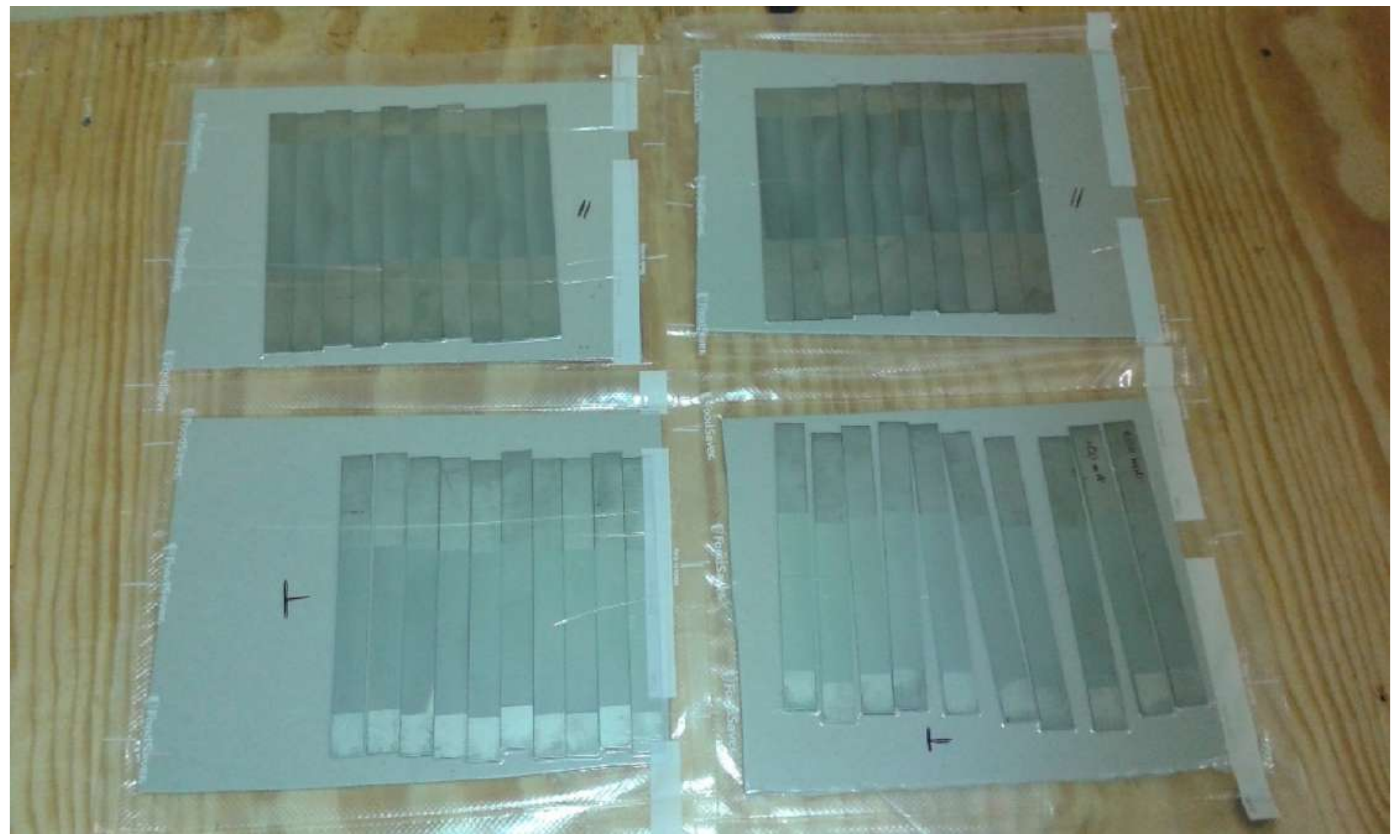


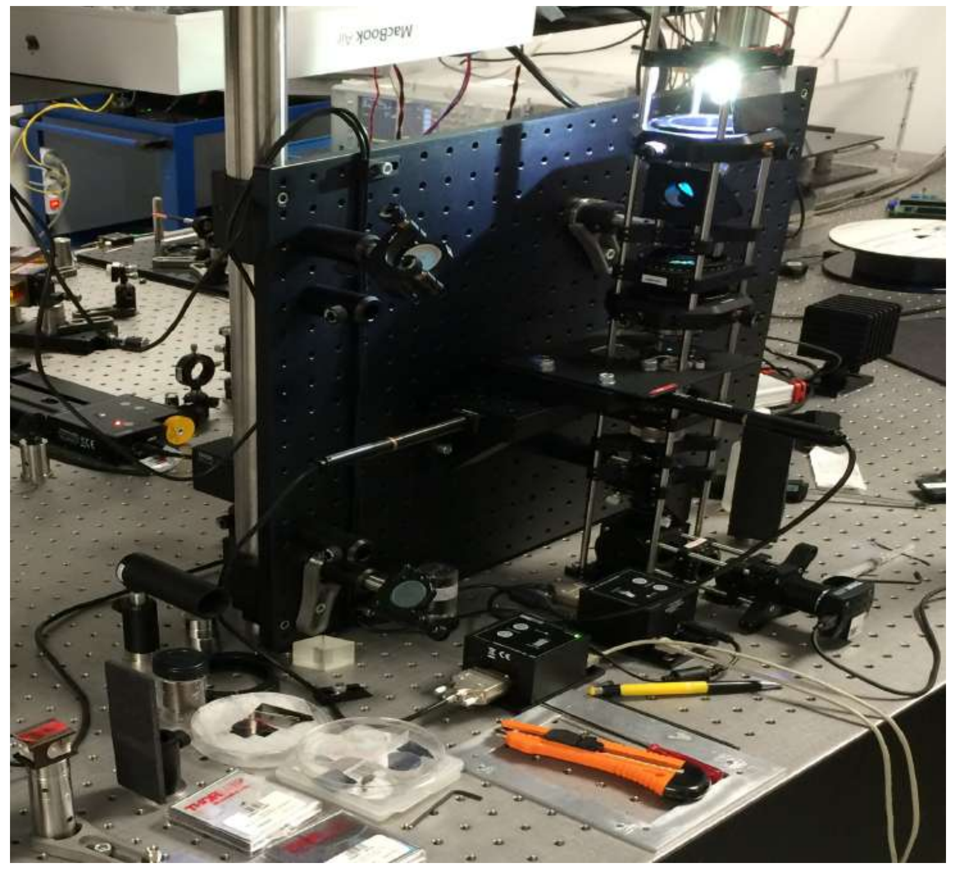
Öktem et al., Nature Photonics 7, (2013)

HR-LIPSS: High Regular Laser Induced Periodic Surface Structures @ DISMI-UNIMORE

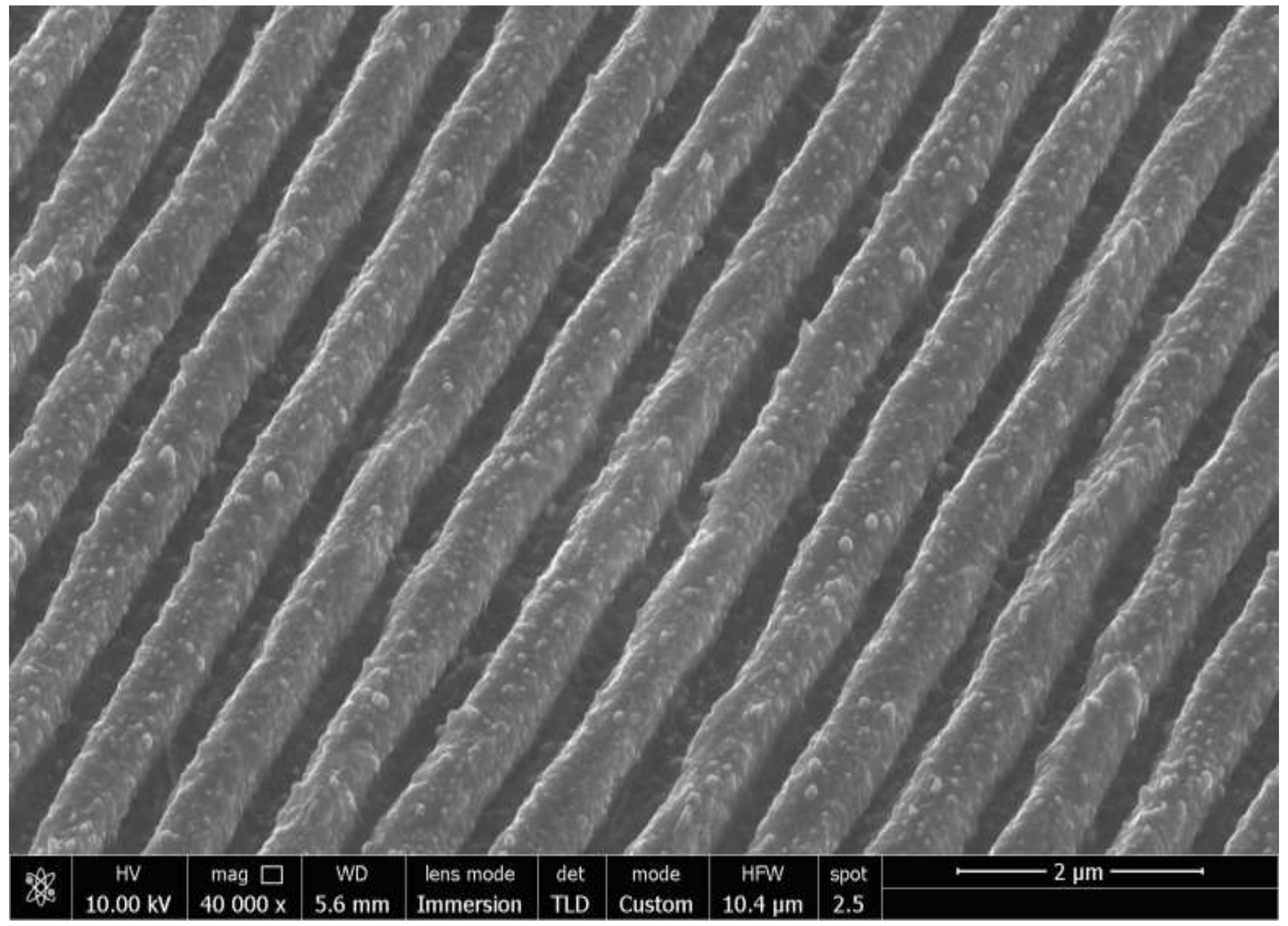
- Periods ~ (0.2 - 0.8) $\lambda/2$
- Large Areas → 4000 mm^2
- Stable and robust process
- High uniform and regular structures
- Productivity > 500 mm^2/min

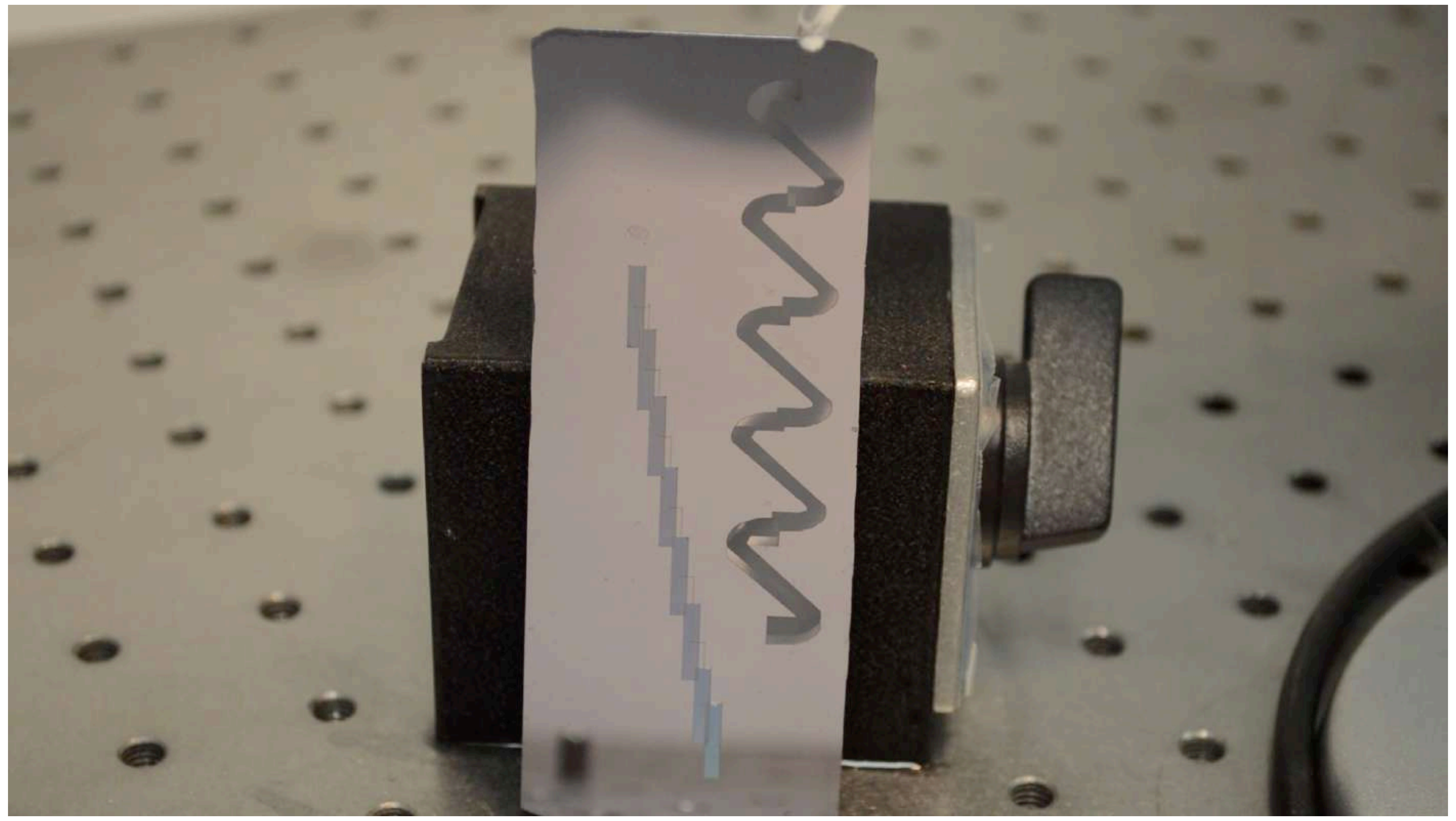


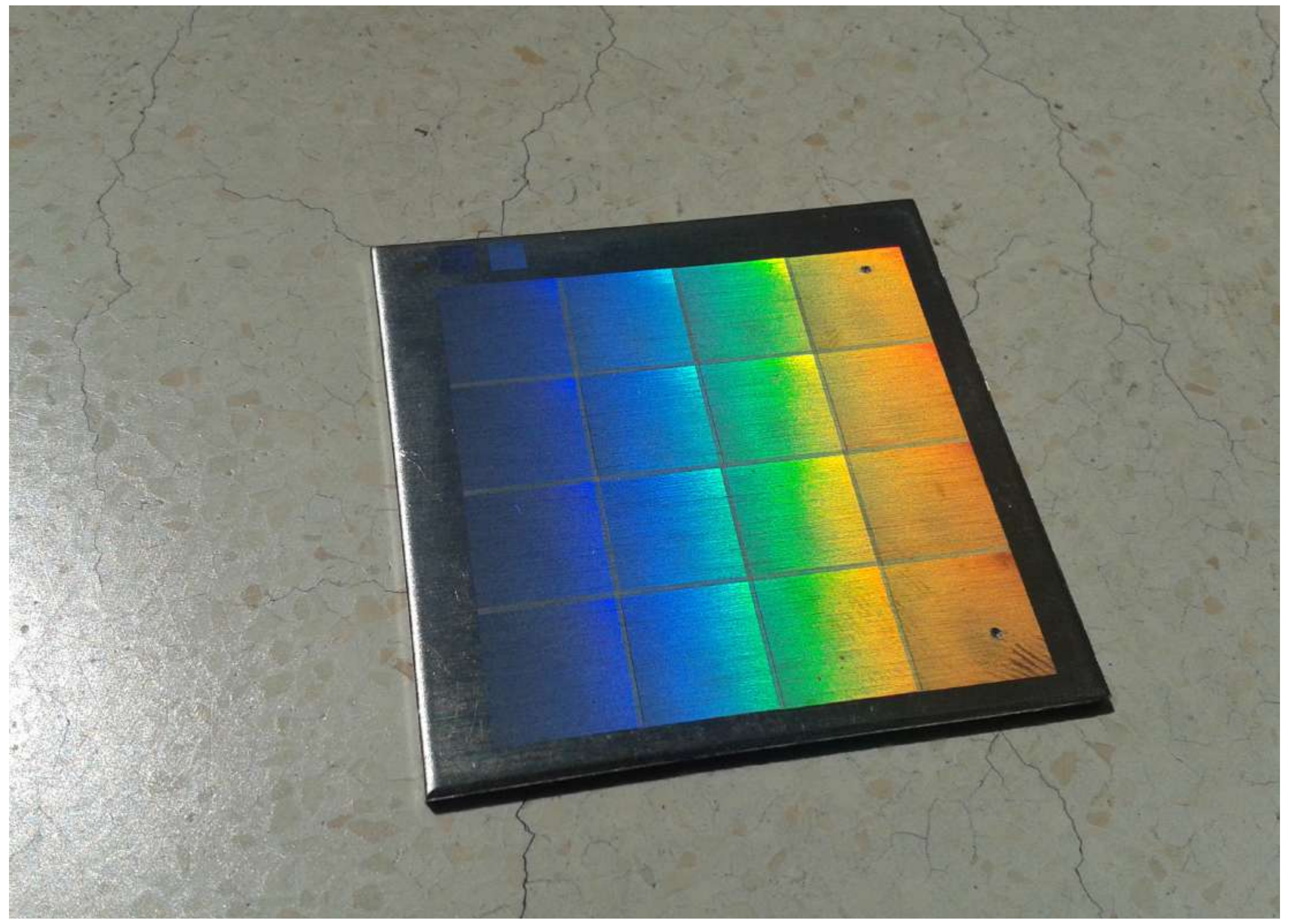


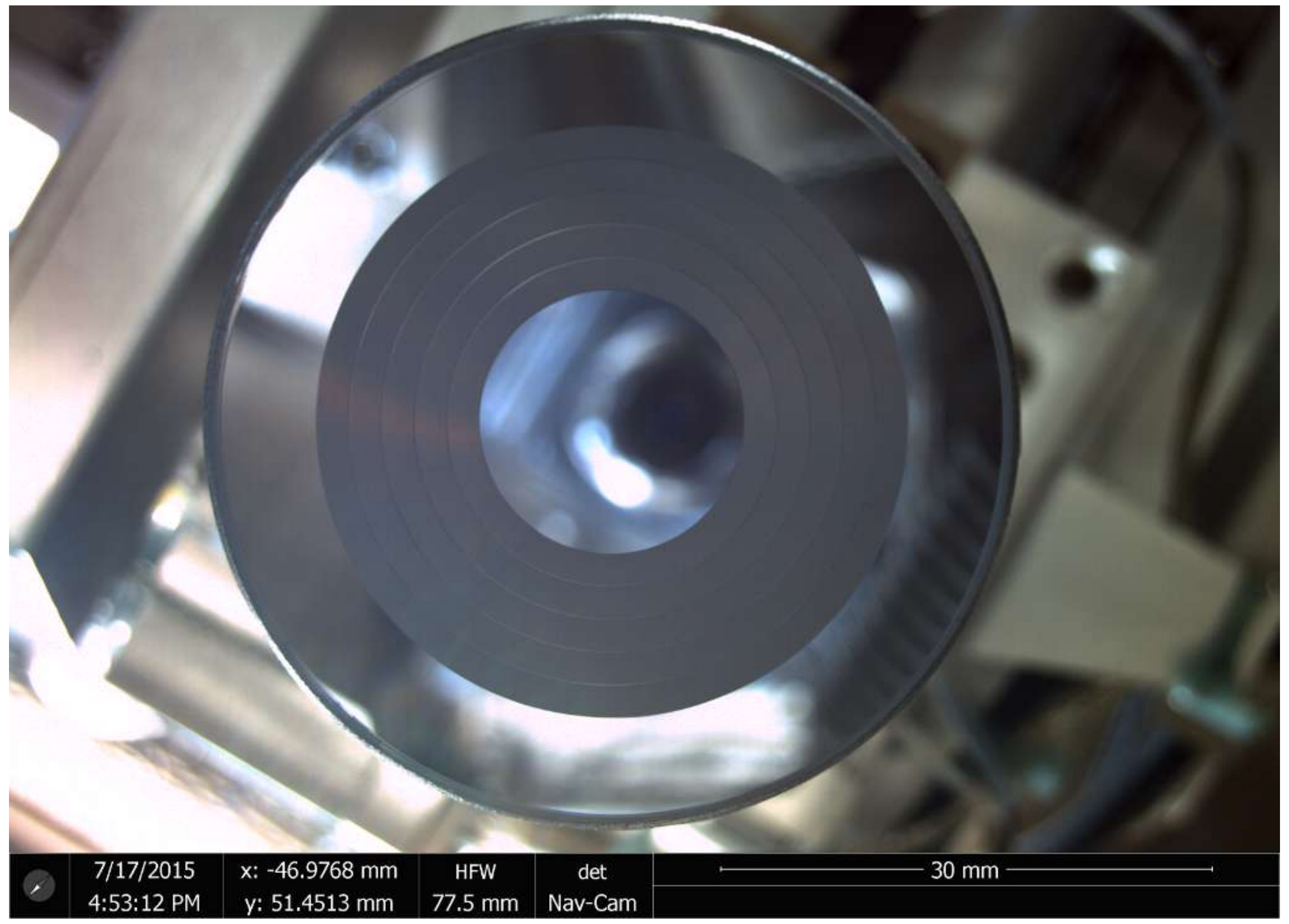


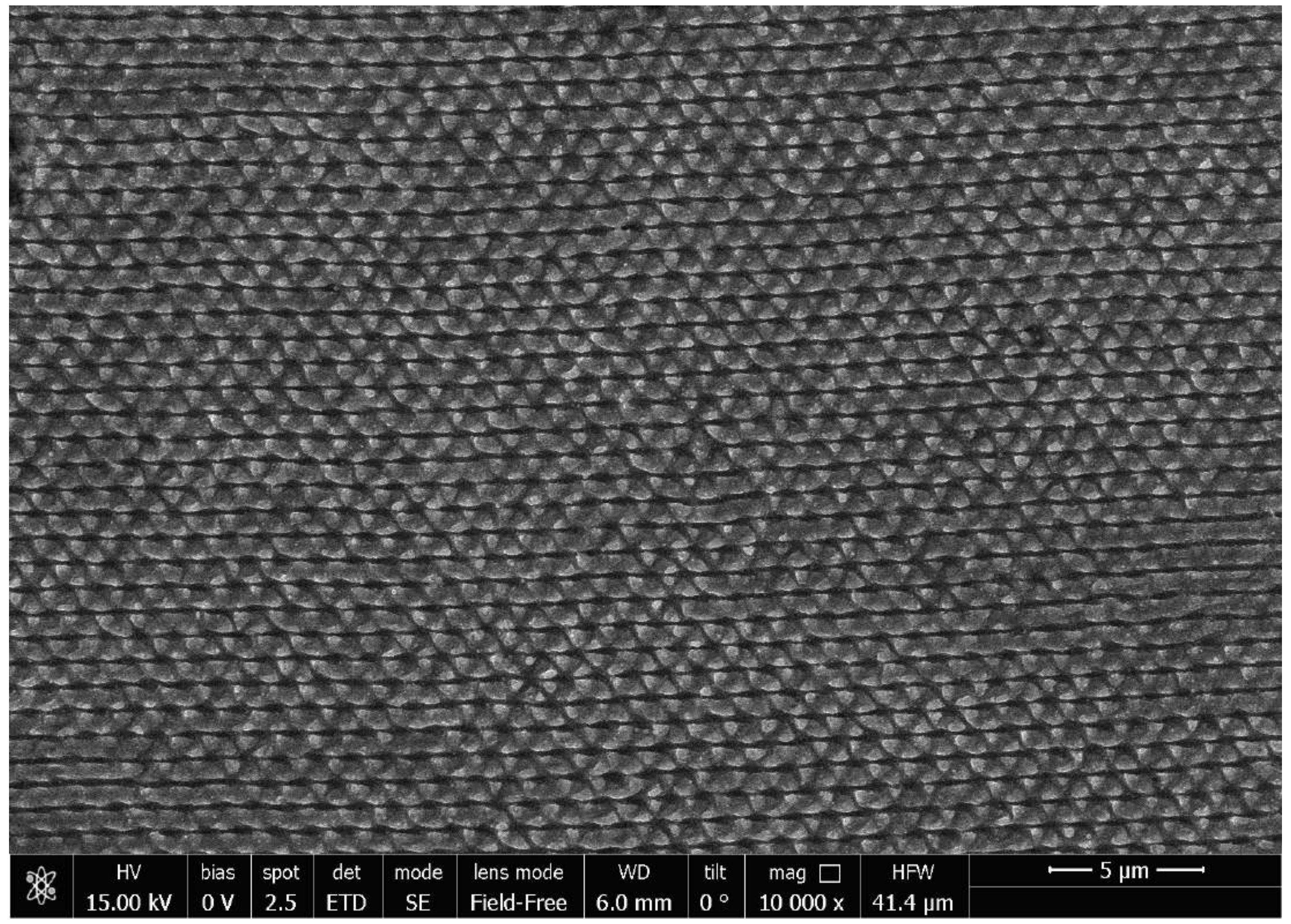
HR-LIPSS: High Regular Laser Induced Periodic Surface Structures @ DISMI-UNIMORE





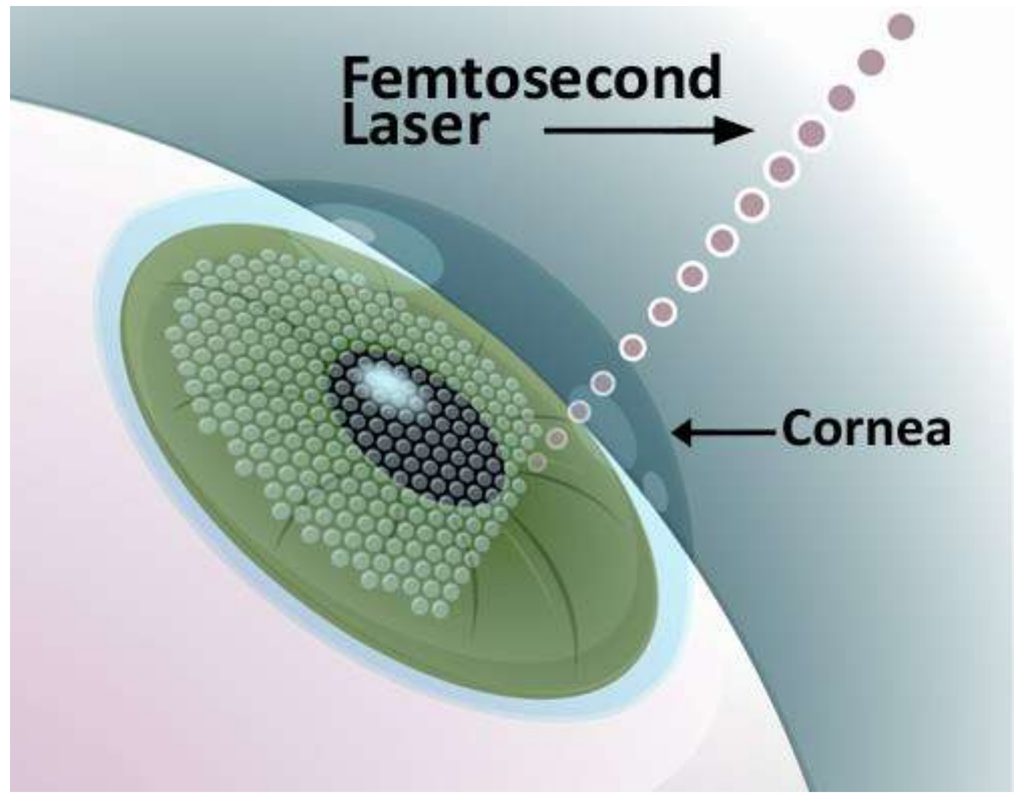




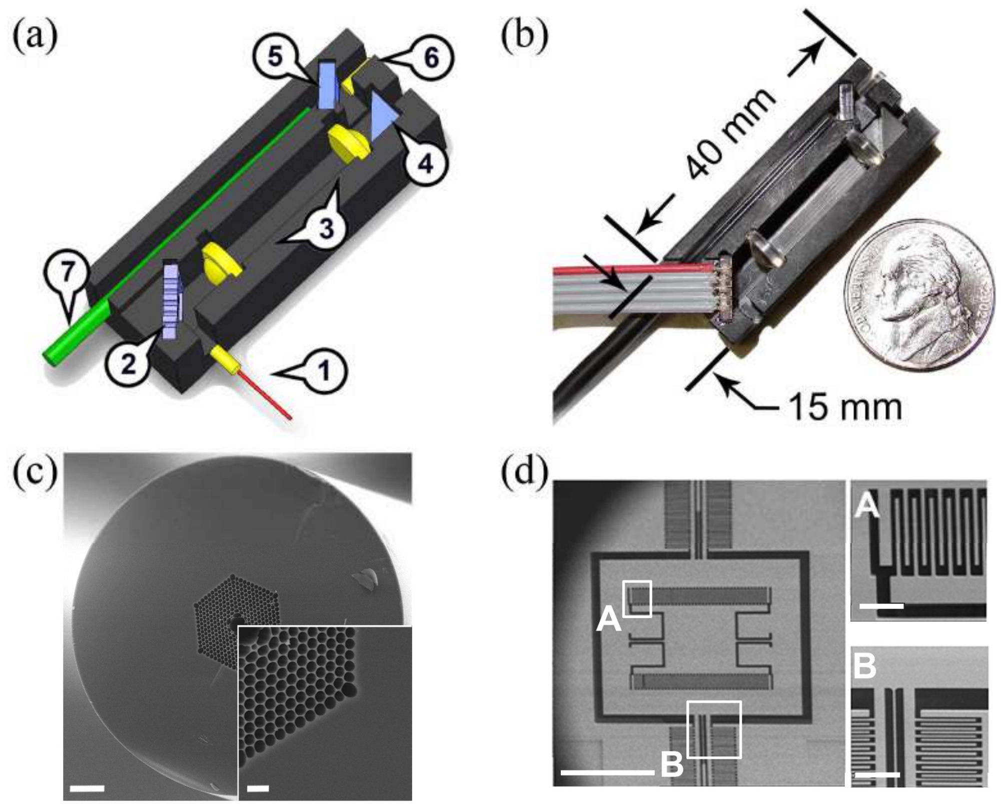


Ultrashort lasers: biomedical applications

SURGERY

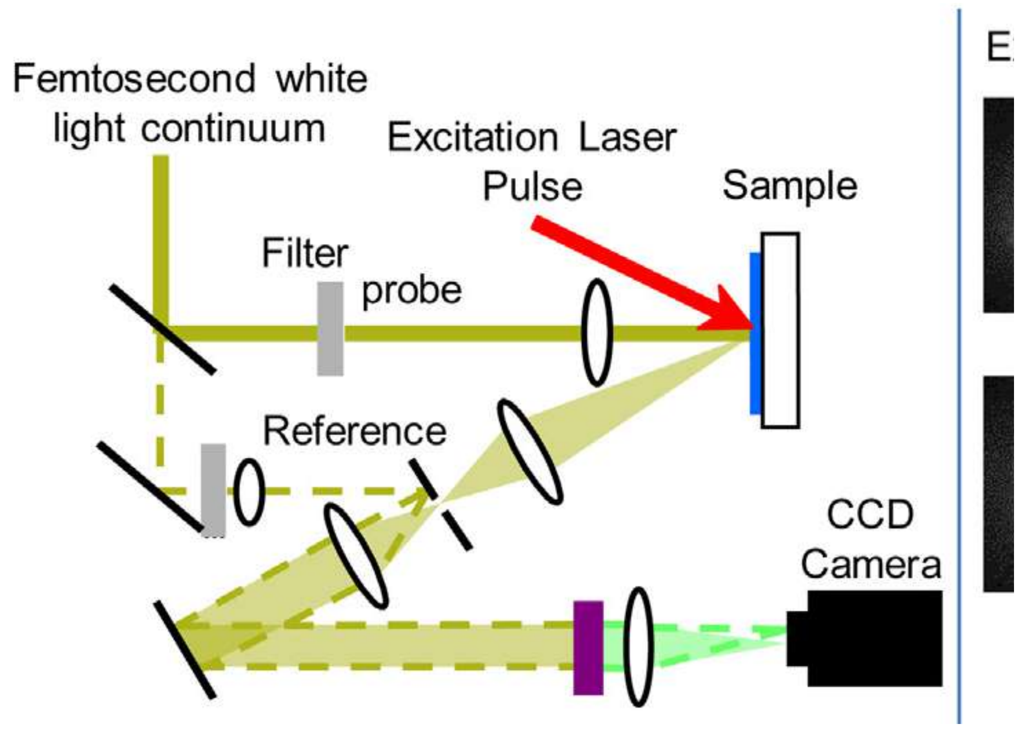


https://goo.gl/images/VQ3fcw

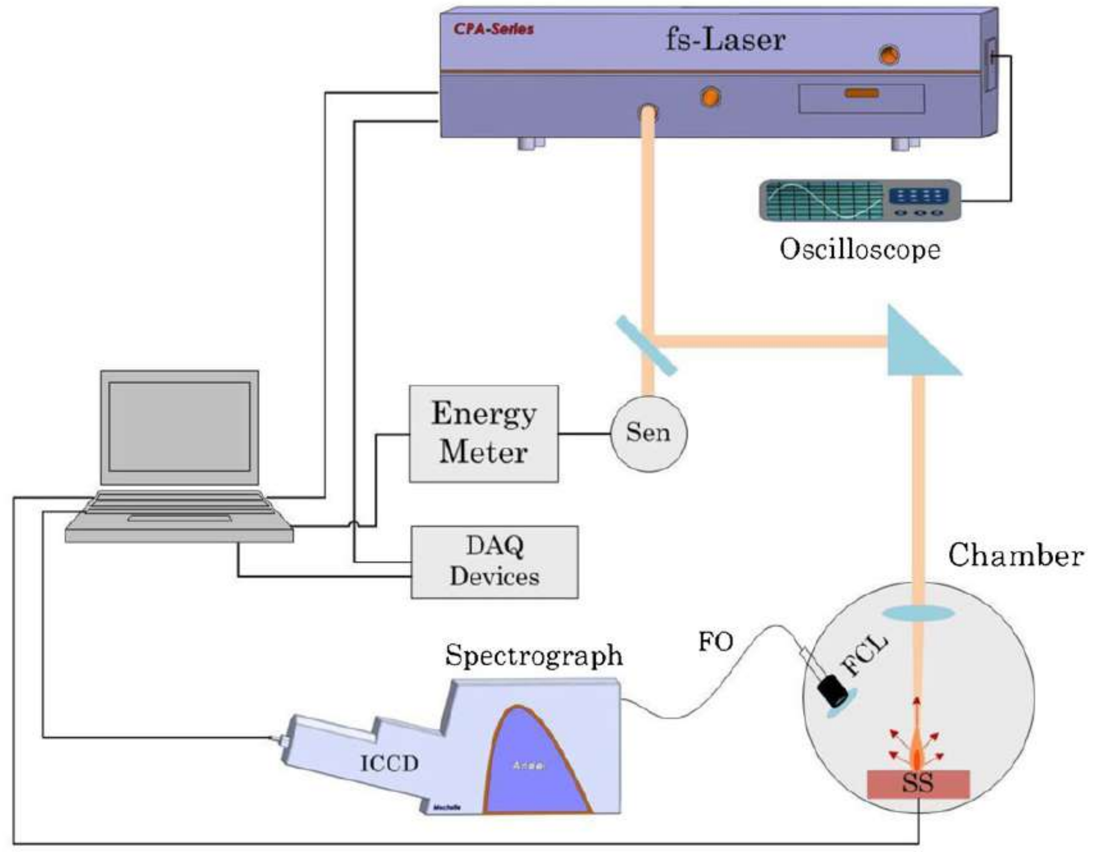


C.L. Hoy Optics Express 2008

DIAGNOSTIC

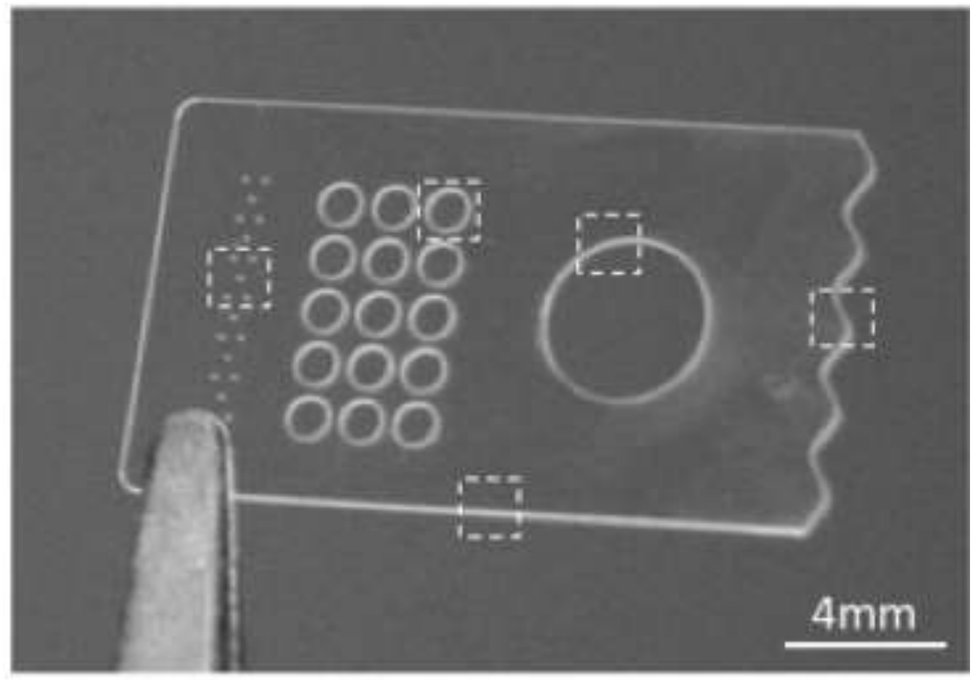


K. Okano et al. Photochemistry Reviews 28 (2016)

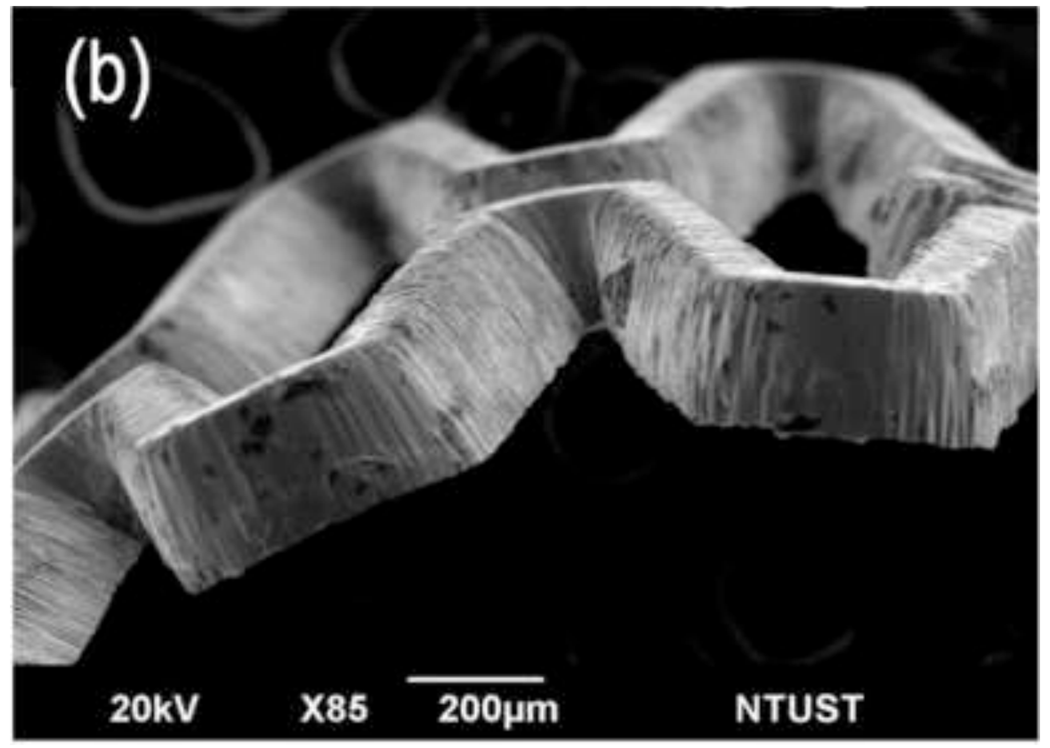


Markushin et al. - Anal Bioanal Chem, 2015

DEVICE MANUFACTURING

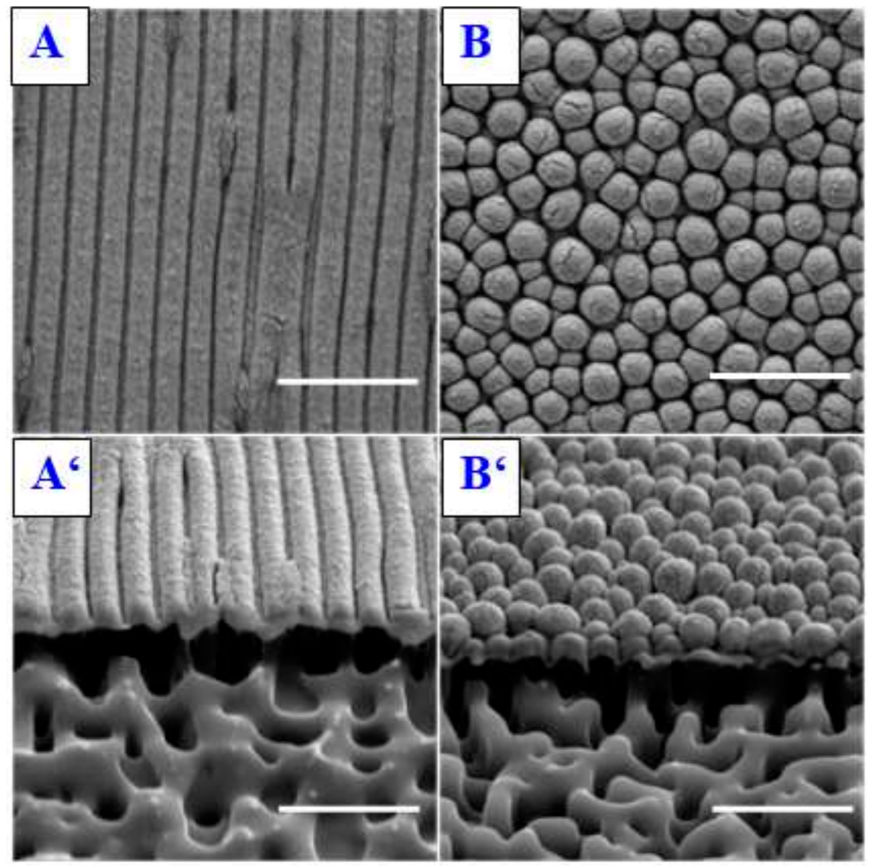


Wlodarczyk et al. - Opt and Lasers in Eng

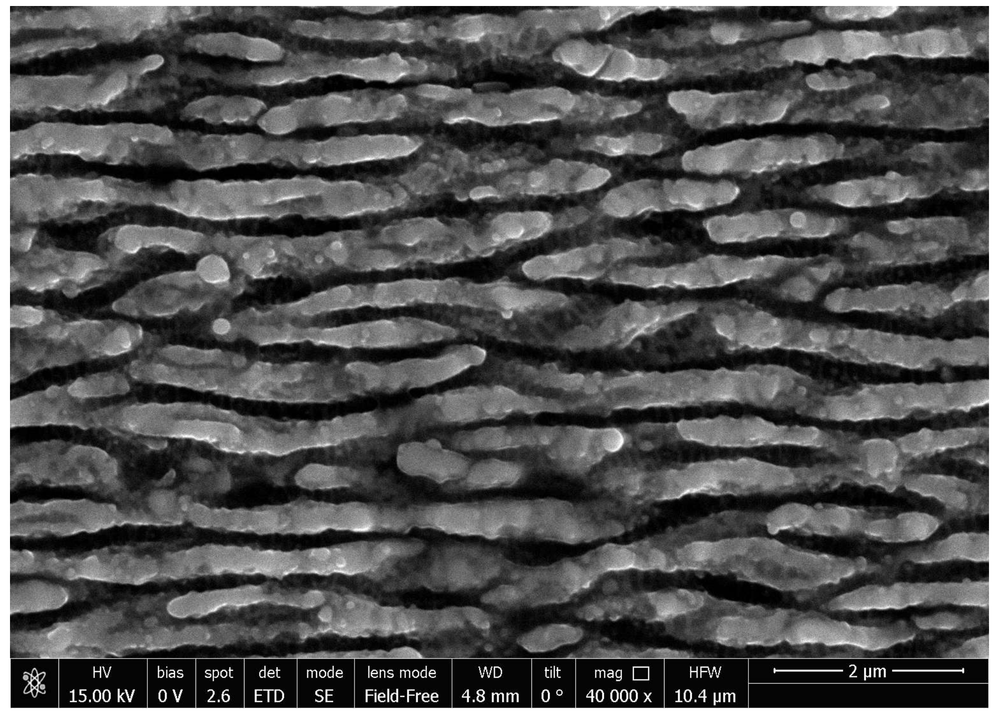


Hung, Chang - Optics & Laser Tech 90, 2017

SURFACE PROCESSING

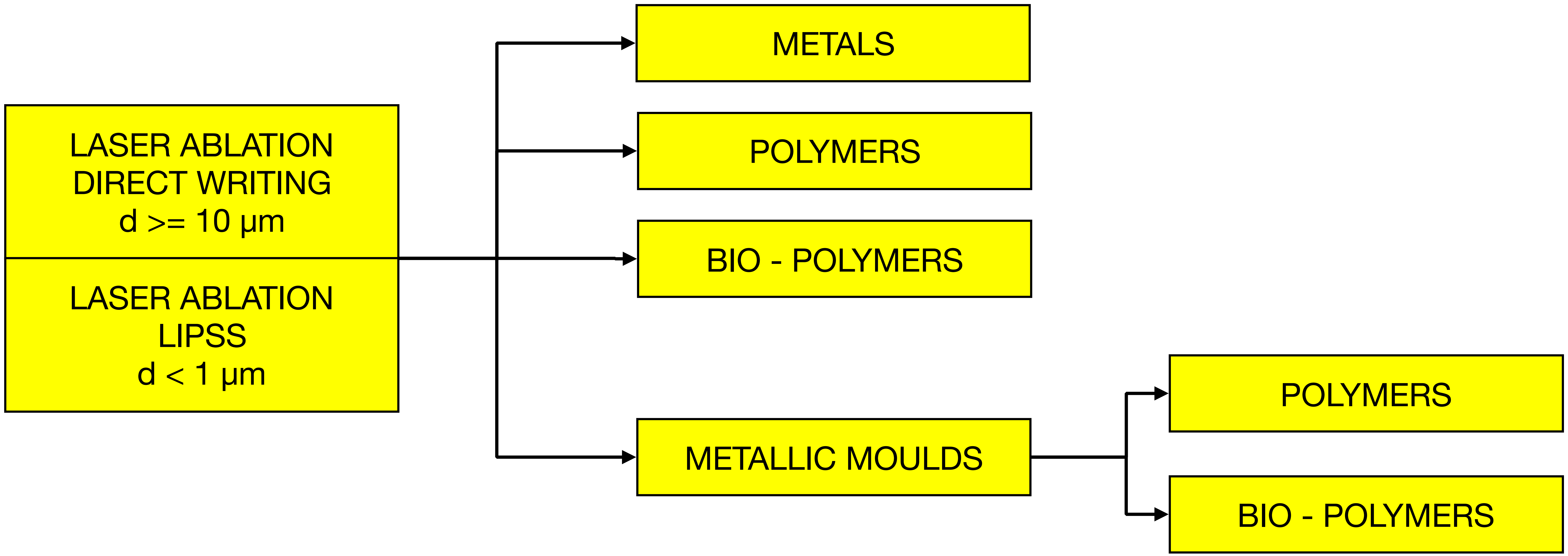


O. Nedela - Materials 2017



I. Gnilitskyi et al - CLEO 2016

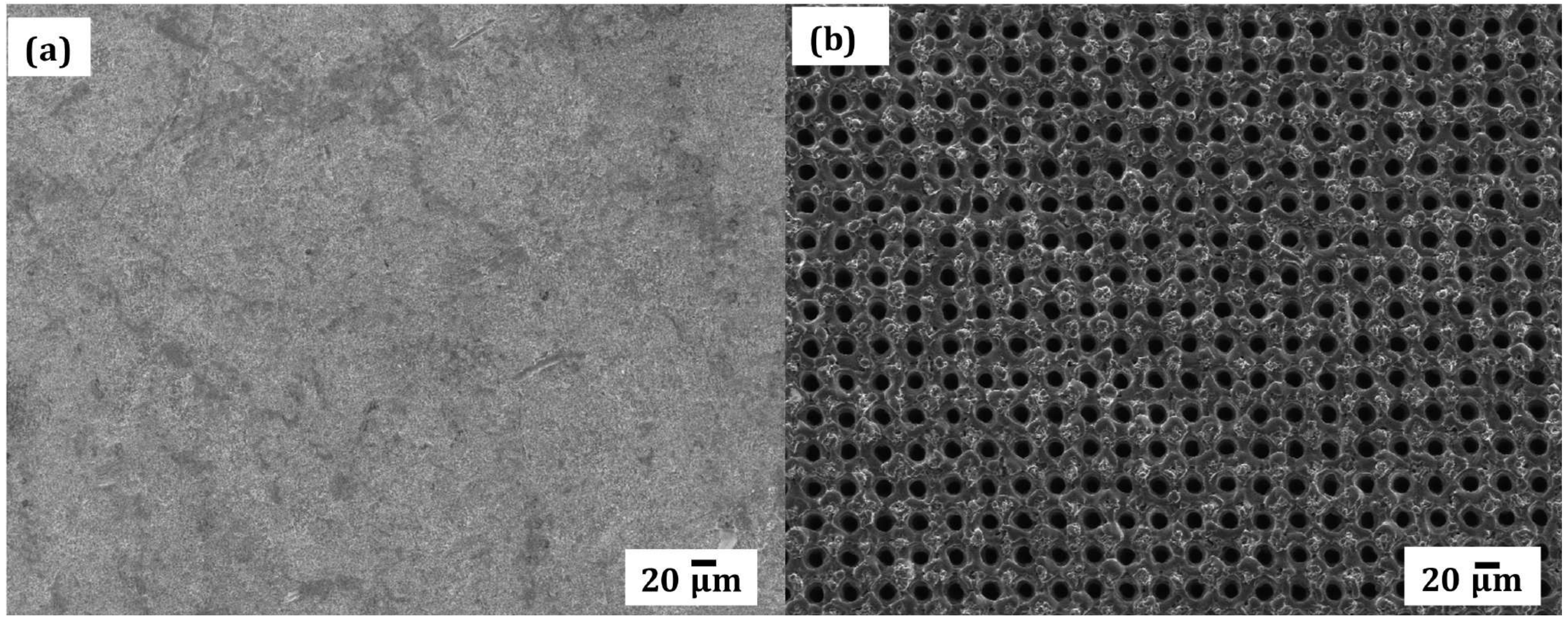
Ultrashort lasers: laser surface texturing



Some examples from literature

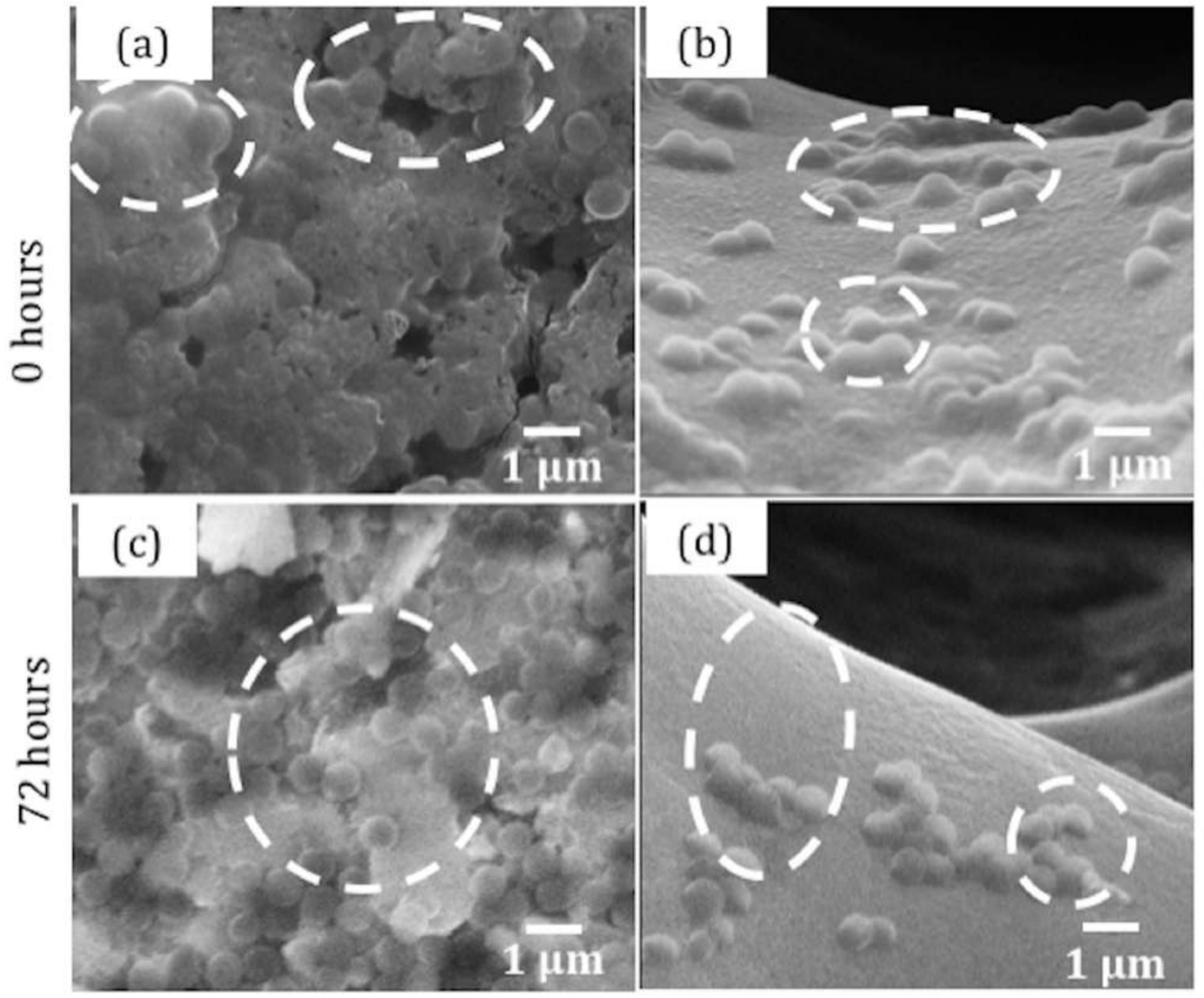
- Currently 10^2 < N. papers < 10^3
- Mainly chosen by the quality of the figures/tables

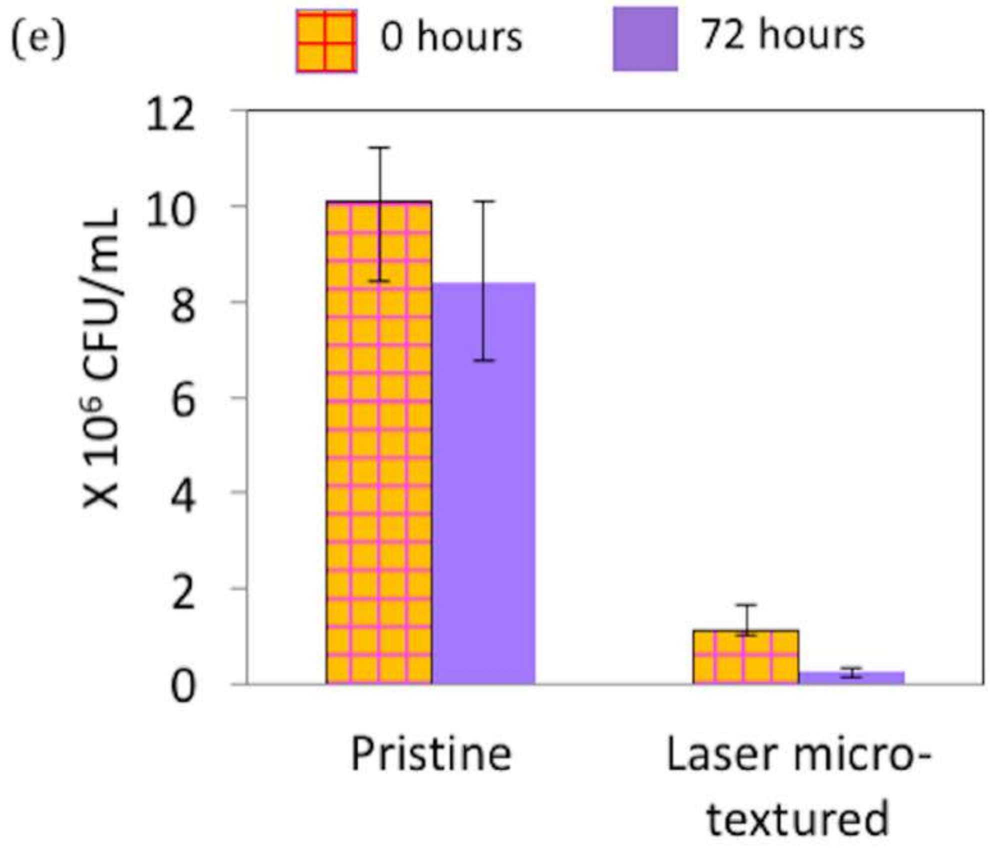
Antimicrobial effects on Ti6Al4V

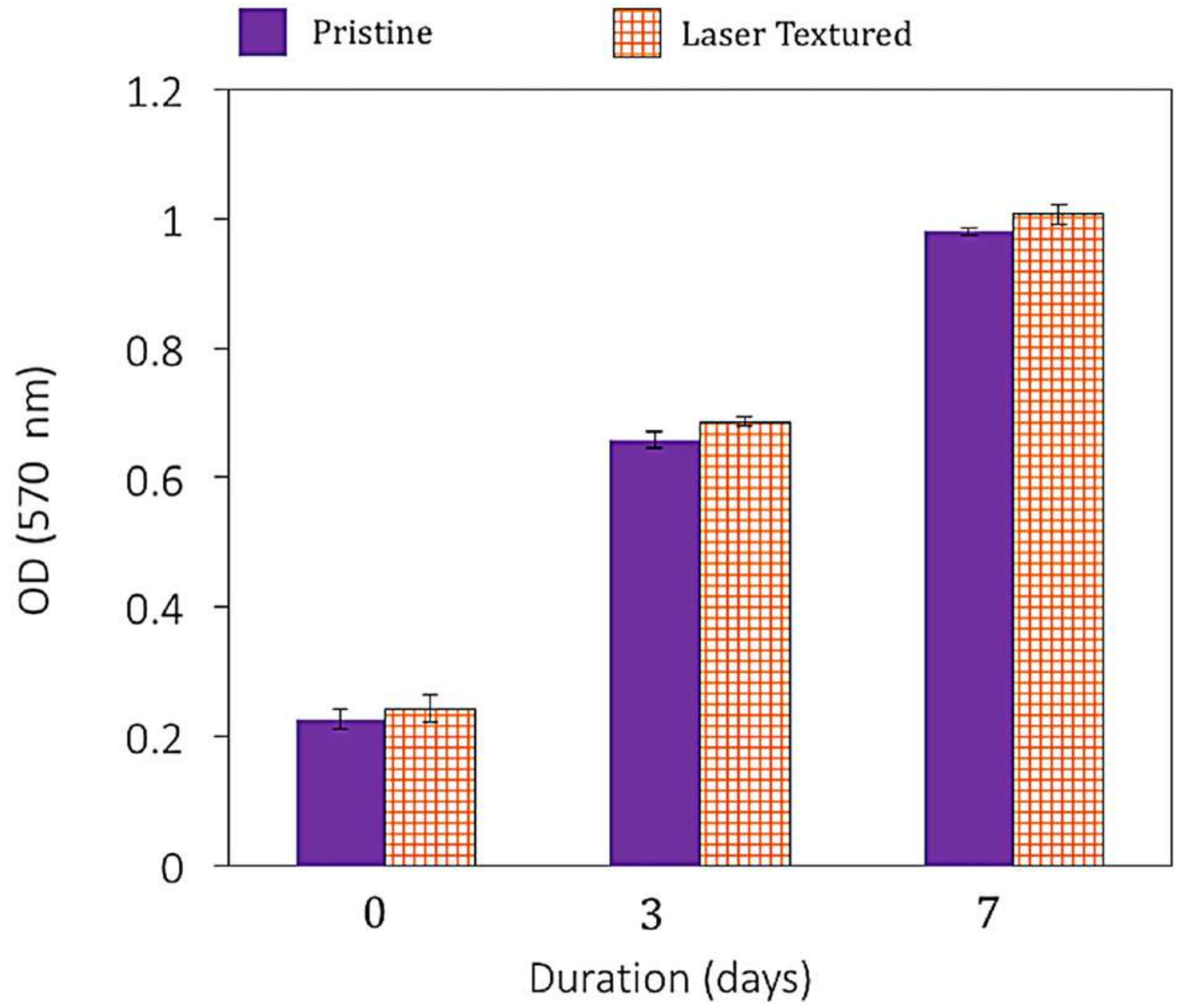


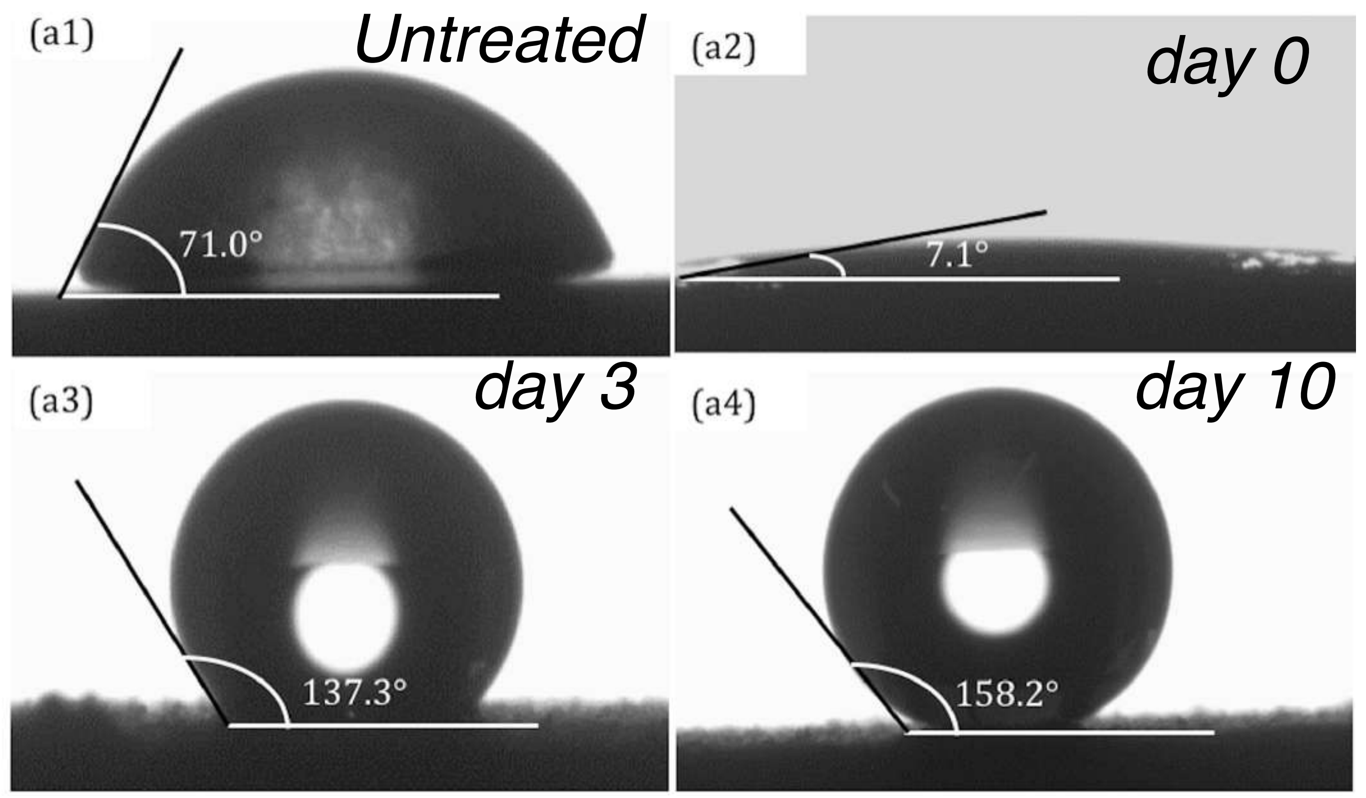
Parmar et al.
Oxidation facilitated antimicrobial ability of laser micro-textured titanium alloy against gram-positive Staphylococcus aureus for biomedical applications
J. Laser Apps. (2018)

Strong reduction of S. Aureos proliferation after a strong ns laser treatment of Ti6Al4V.
Cytotoxicity does not significantly increase as blood coagulation appears not affected.
Relationship with wettability?

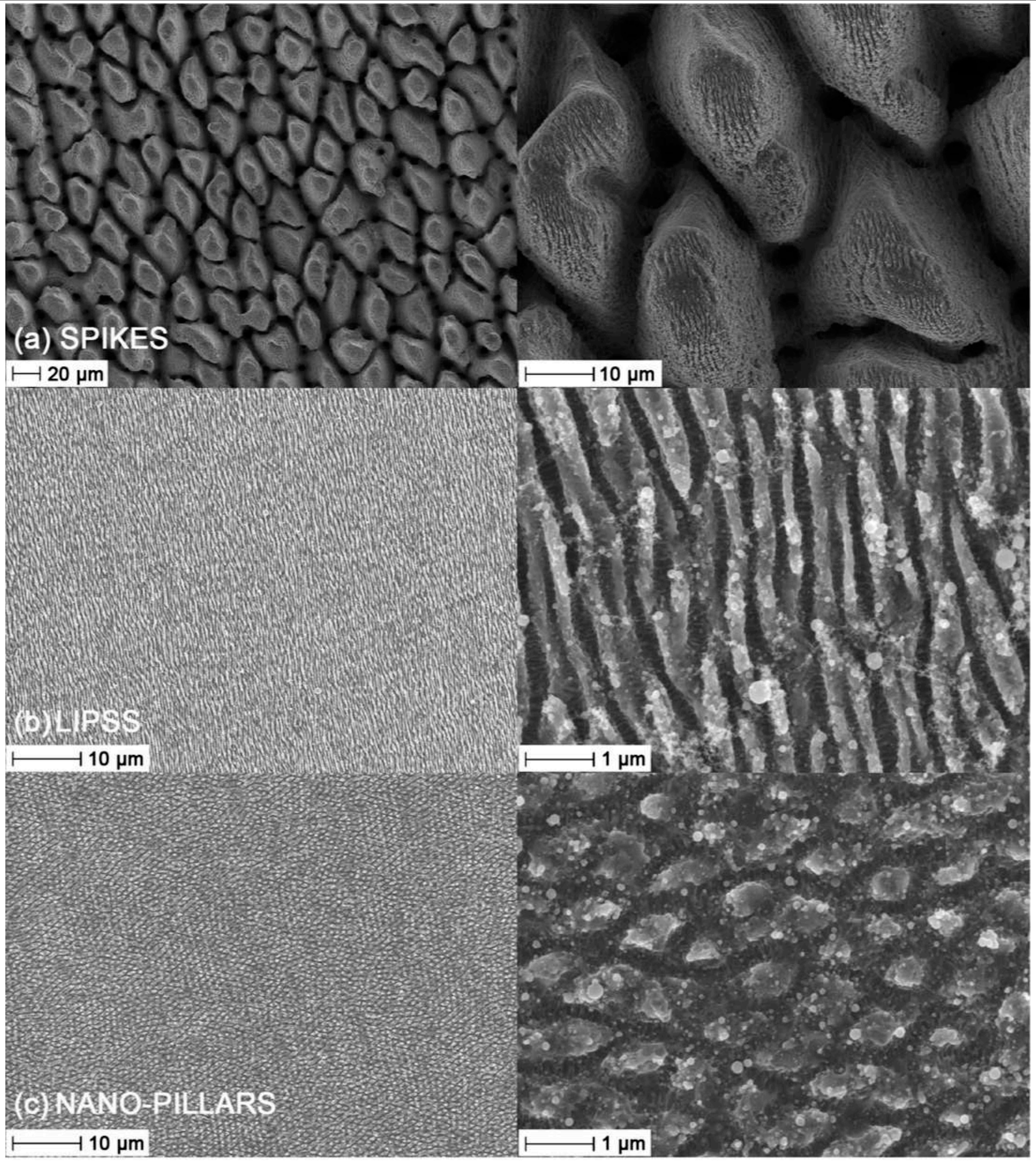






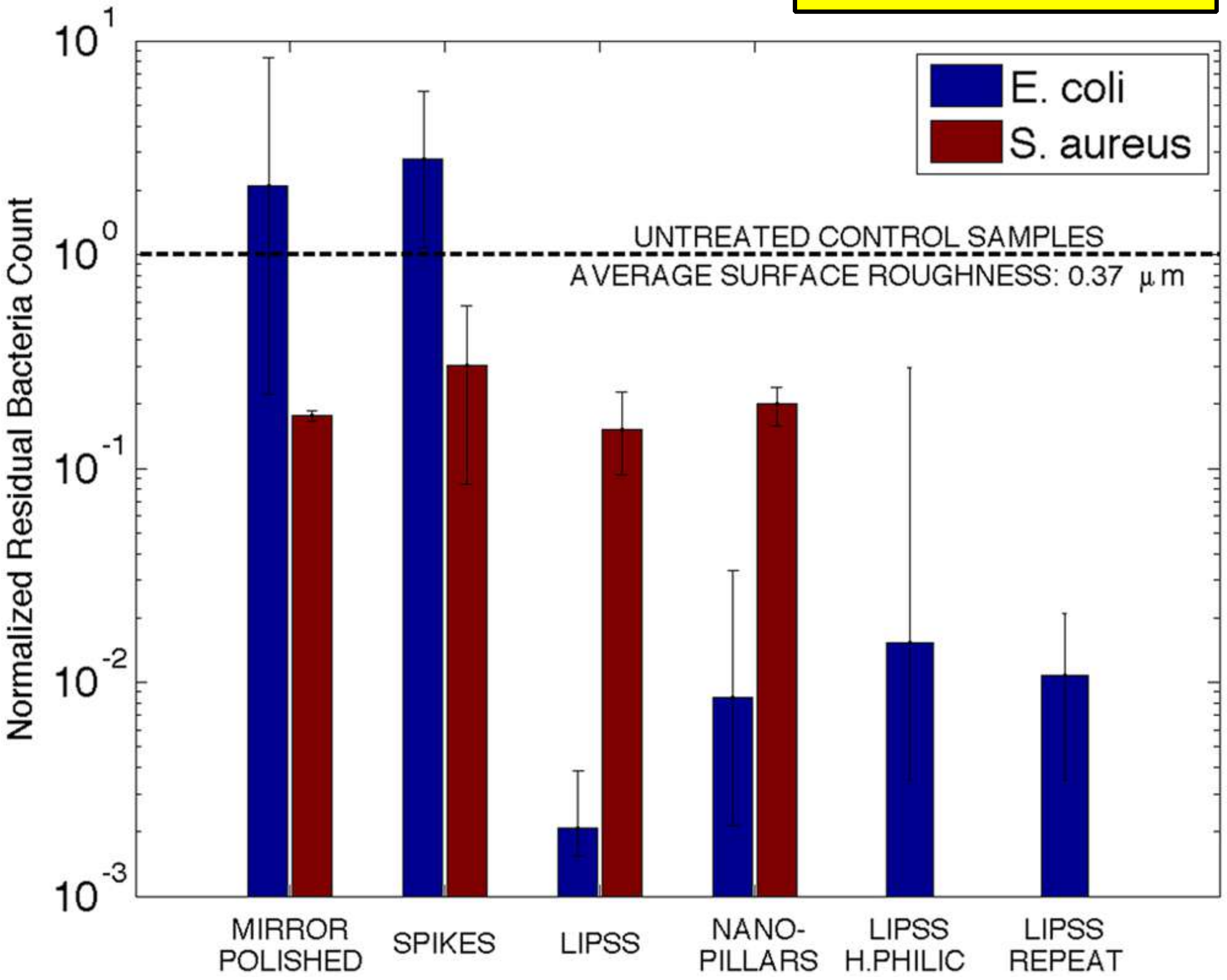


Antibacterial effects on stainless steel AISI 316L

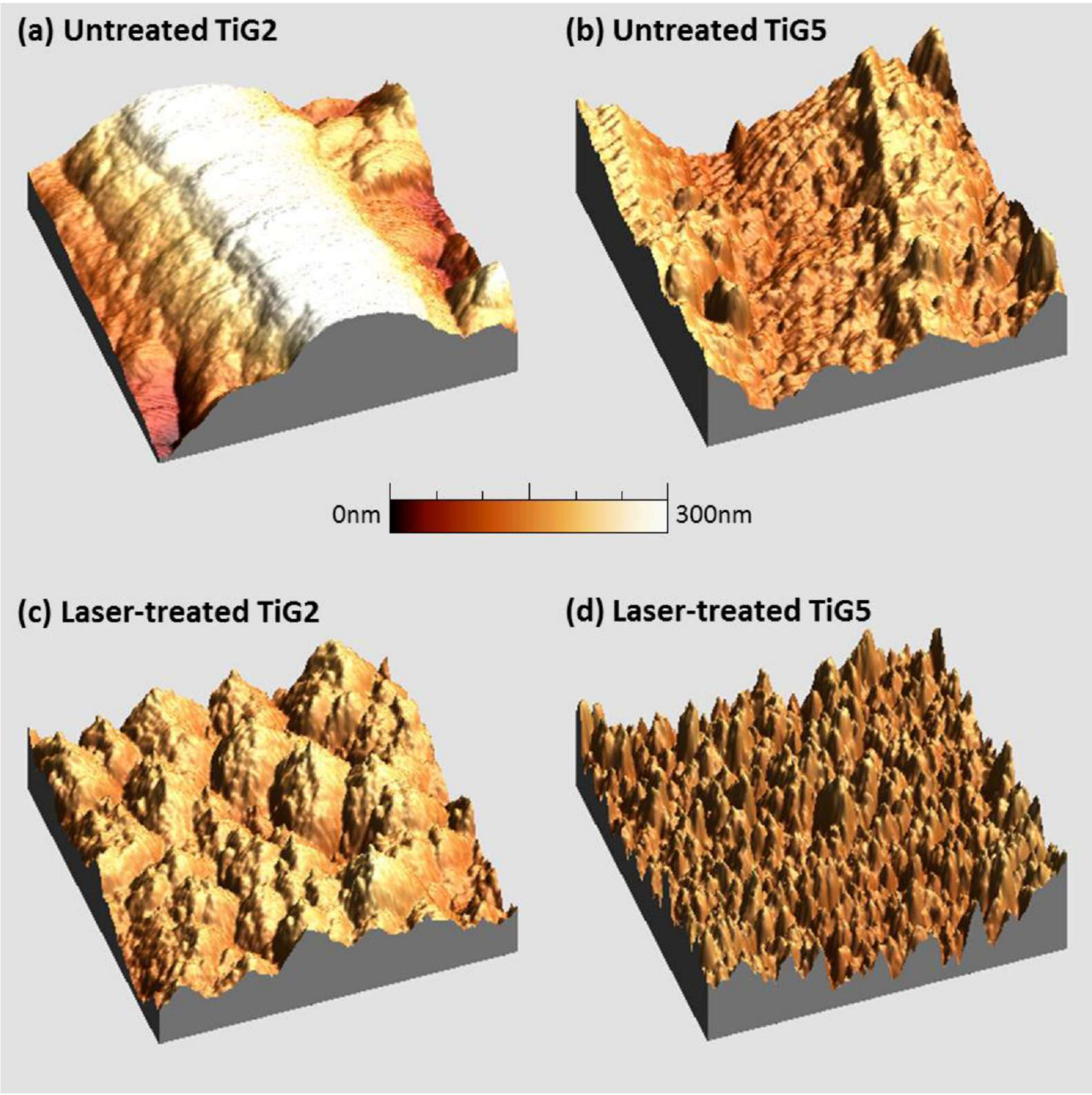


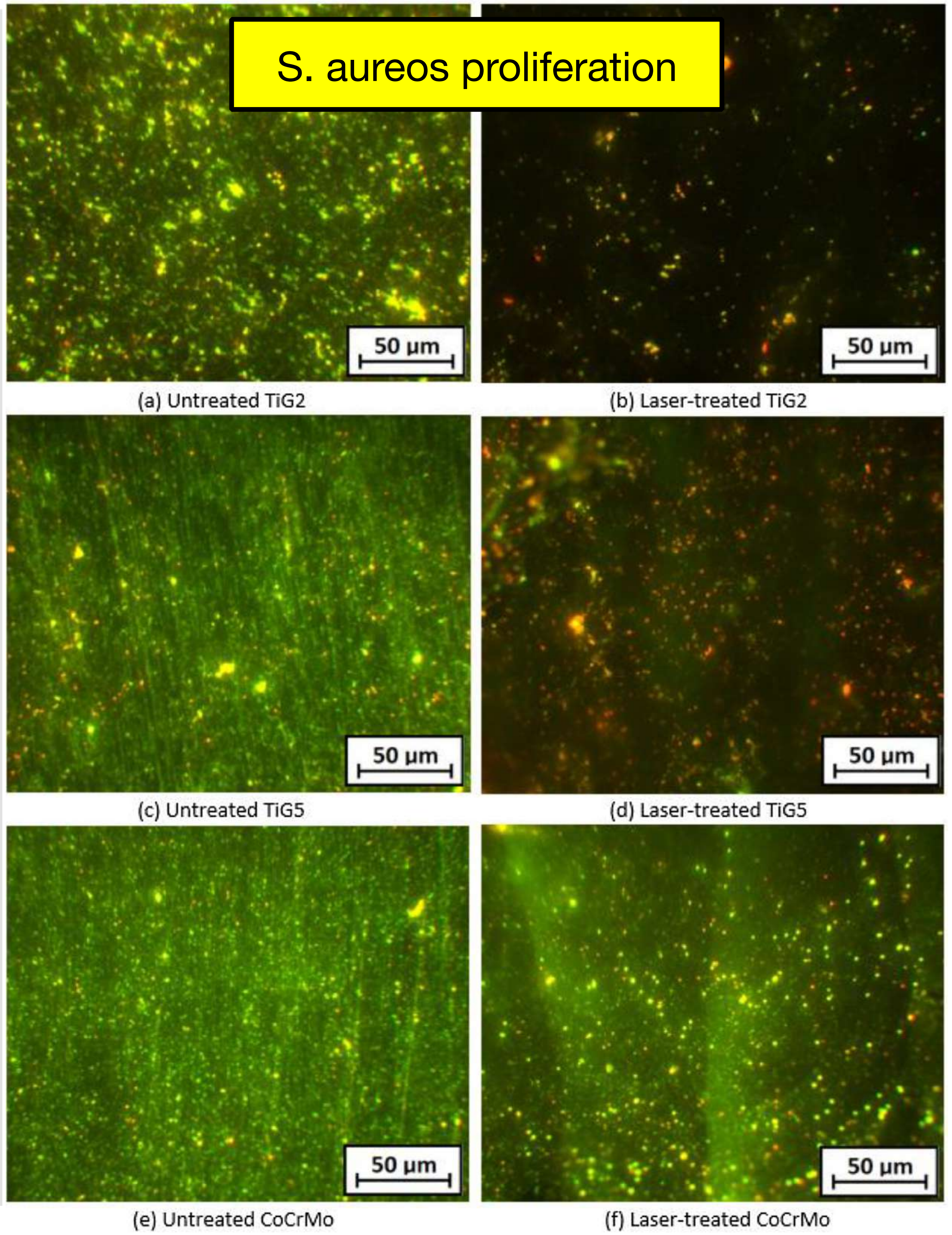
A. H. Lutey et al.
Towards Laser-Textured Antibacterial Surfaces
Scientific Reports (2018)

Strong correlation with hydrophobicity



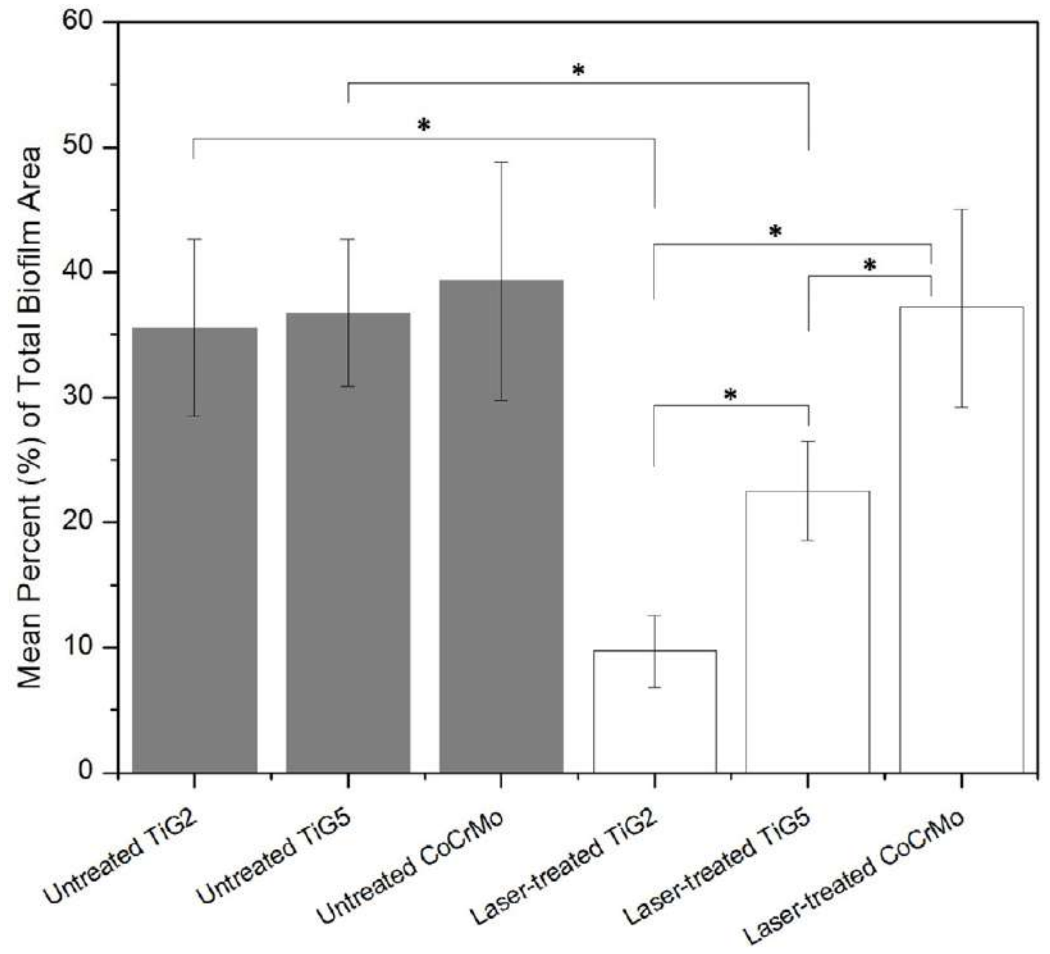
Antibacterial effects on Ti, Ti6Al4V and CoCrMo orthopaedic implant alloys





C.W. Chanet al.
Enhancing the antibacterial performance of orthopaedic implant materials by fibre laser surface engineering
Applied Surface Science (2017)

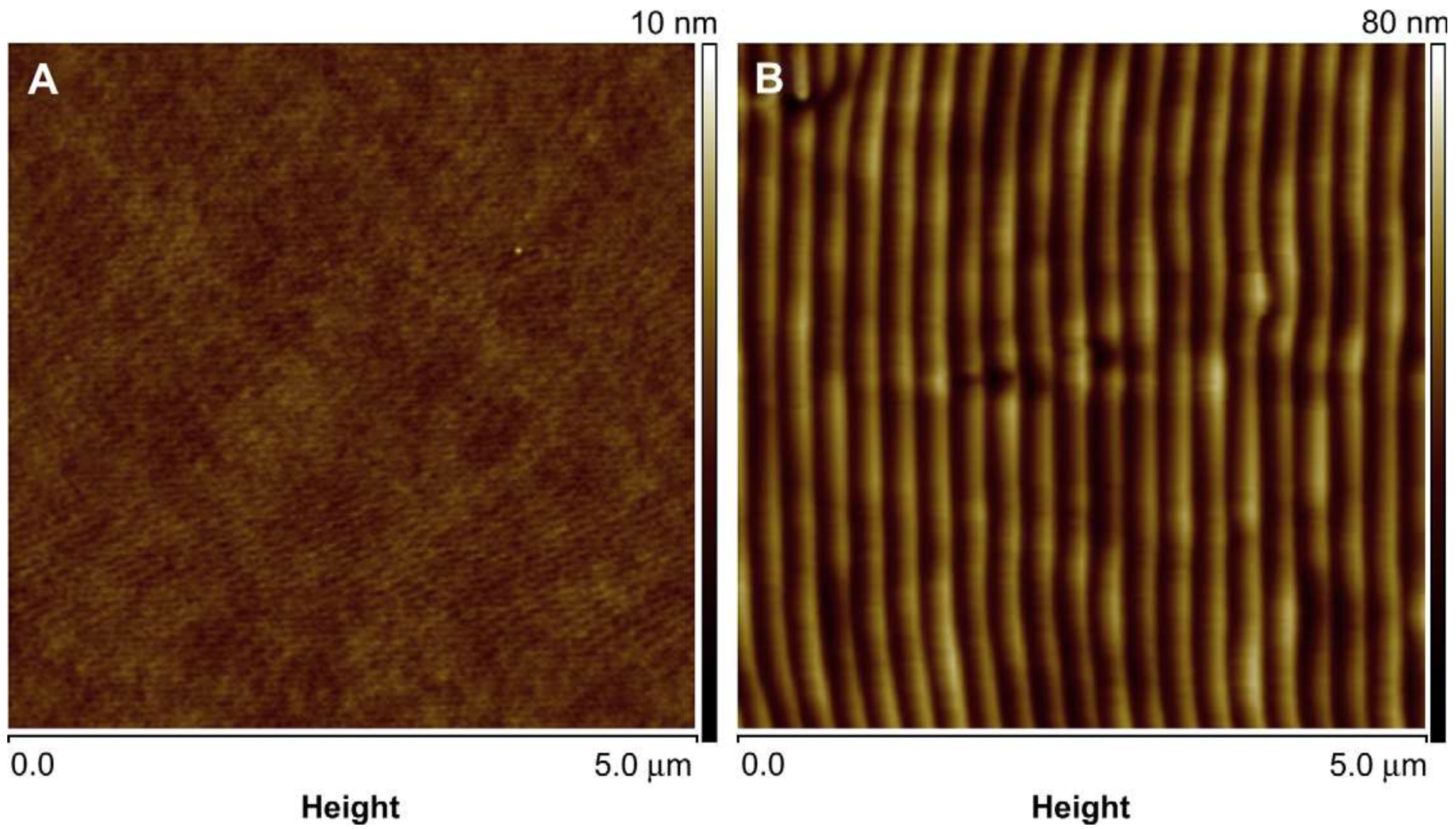
CW 1064 nm Fiber laser under N2 shielding gas.
Mainly an oxidation process
This can explain stronger results on prone to oxidation Ti based alloys compared to CoCrMo

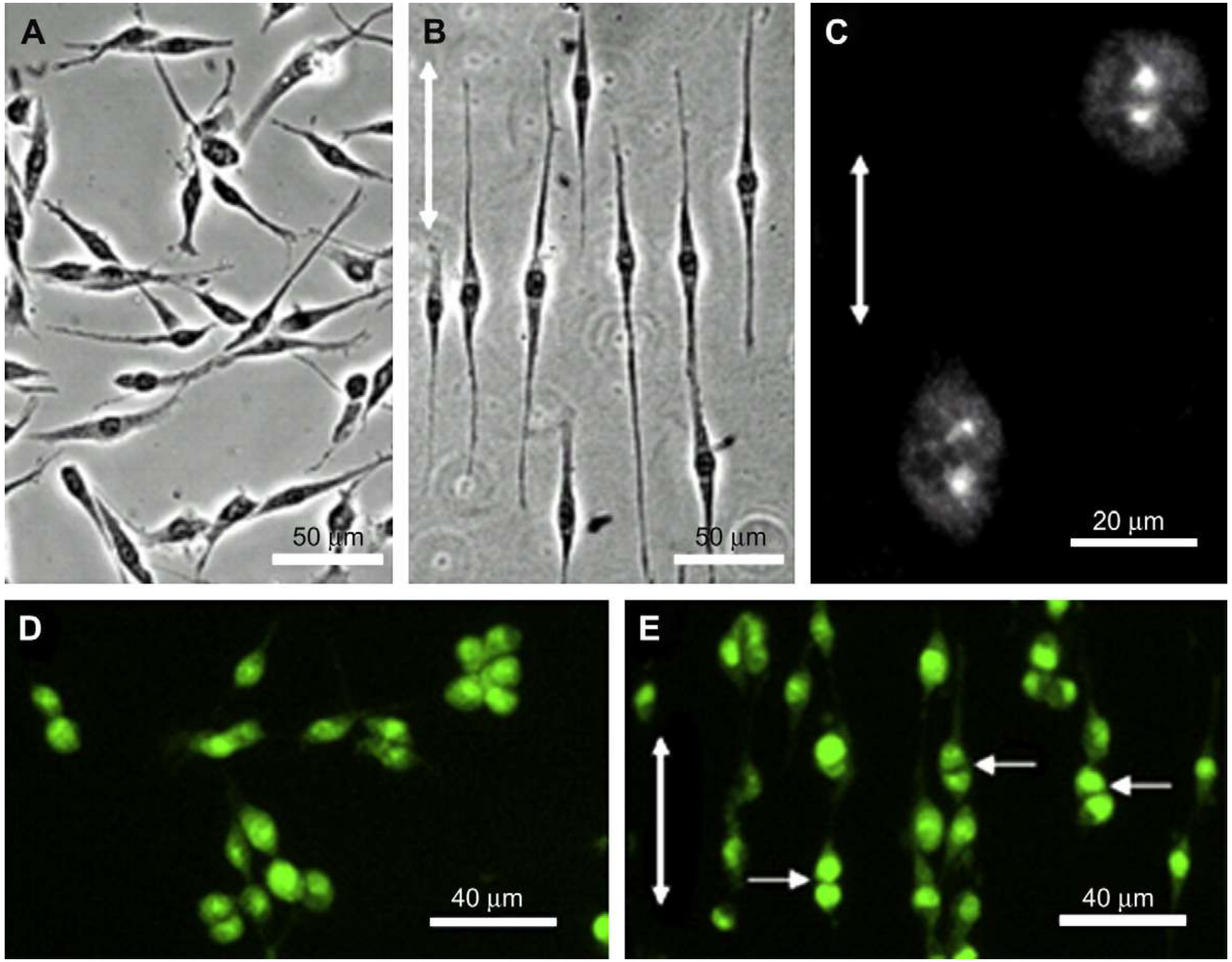


Cell proliferation orientation on PS

Wang et al.
Cell directional migration and oriented division on three-dimensional laser-induced periodic surface structures on polystyrene
Biomaterials (2008)

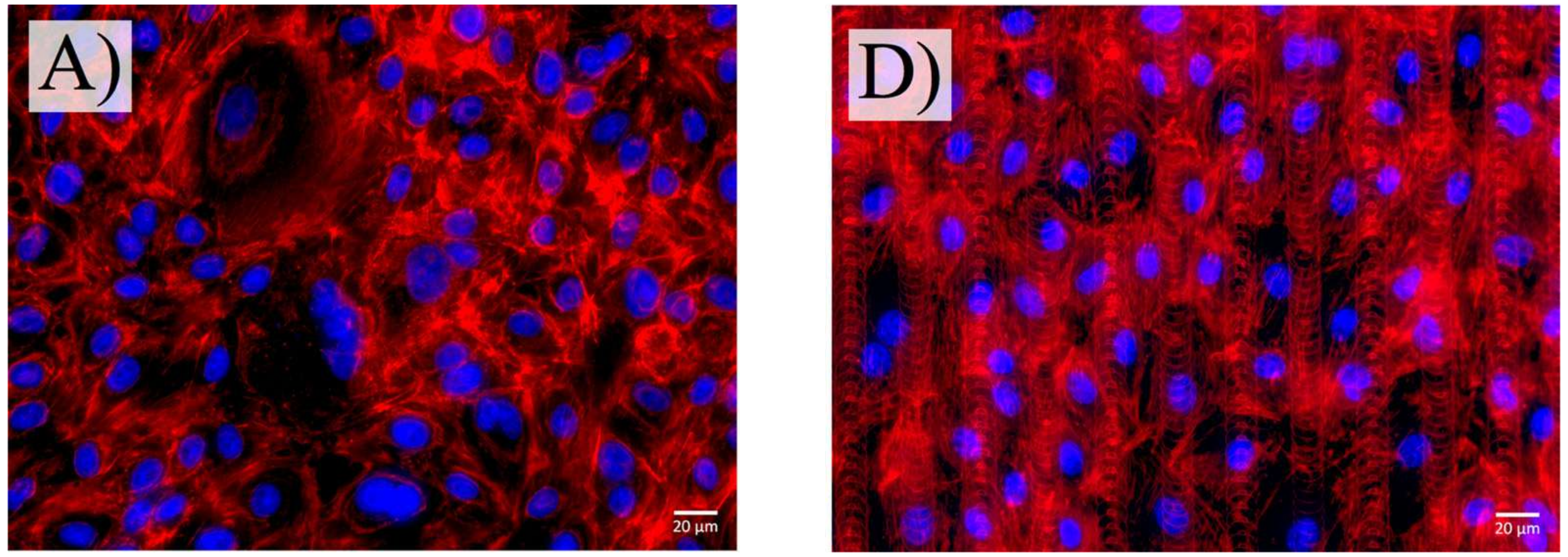
Generation of LIPSS on Polystyrene
C6, HeLa and SPCA-1 cells mgration oriented division
A untreated
B treated
Double arrow line -> LIPSS orientation



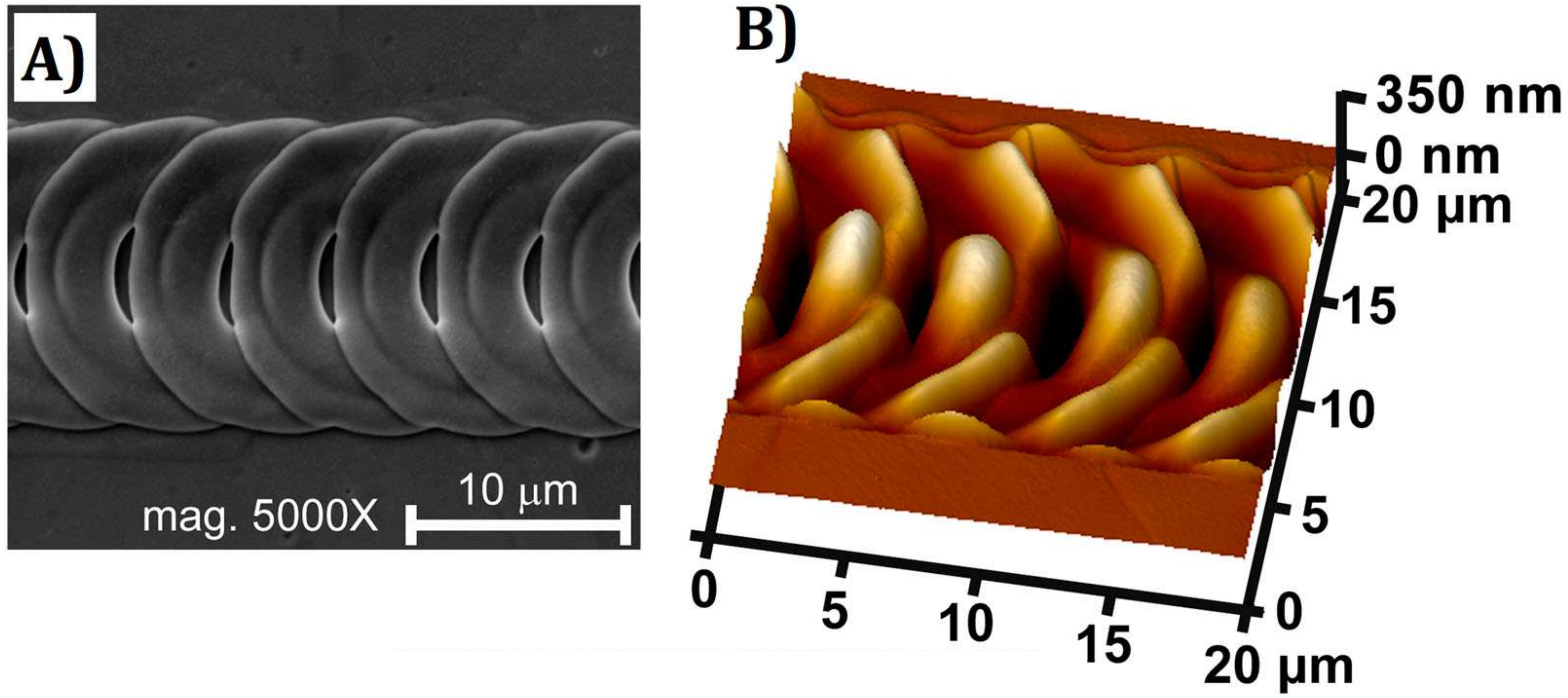


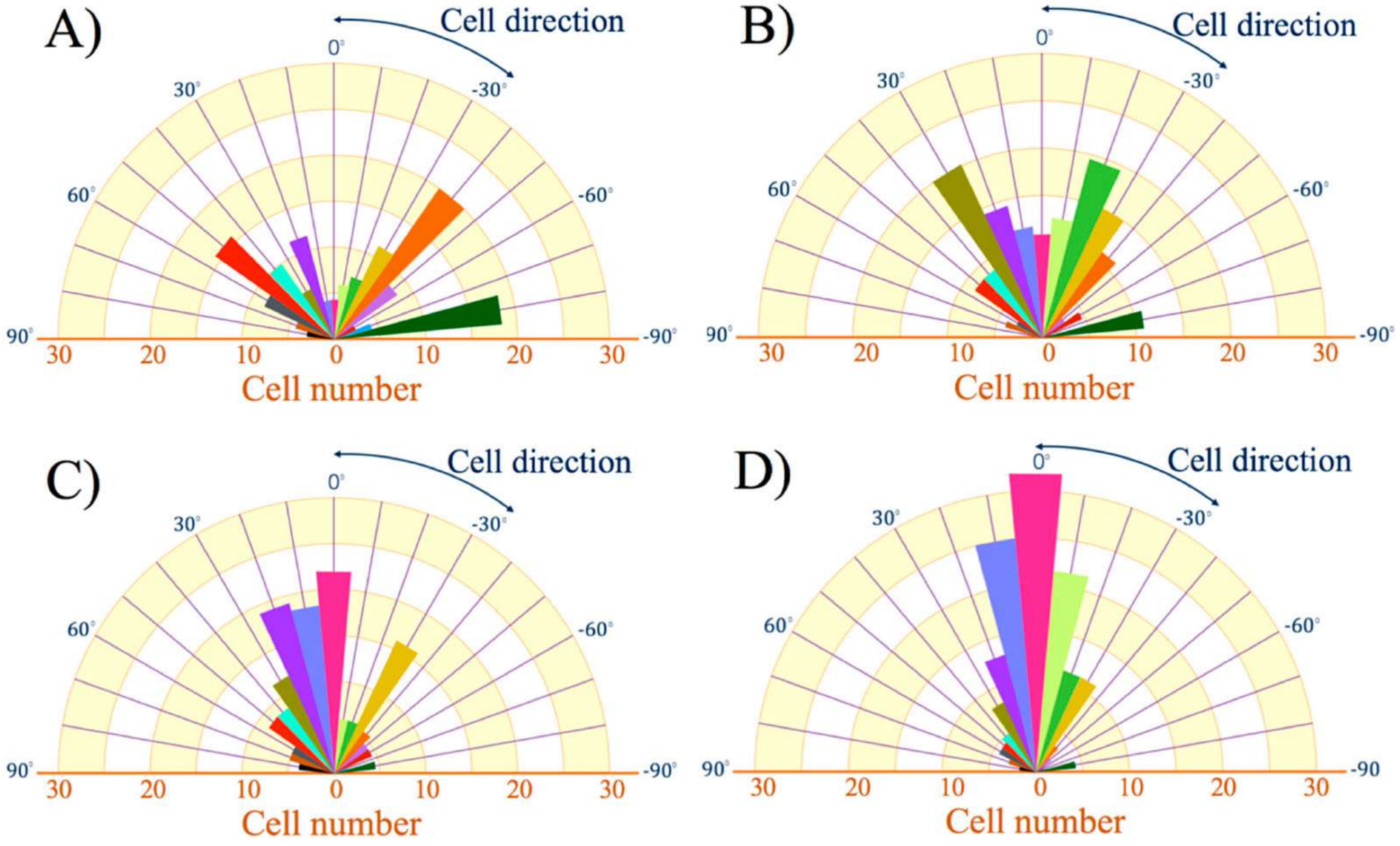
Cell proliferation orientation on SS316L

Purnama et al.
Laser surface texturing of SS316L for enhanced adhesion of HUVECs
Surface Engineering (2018)

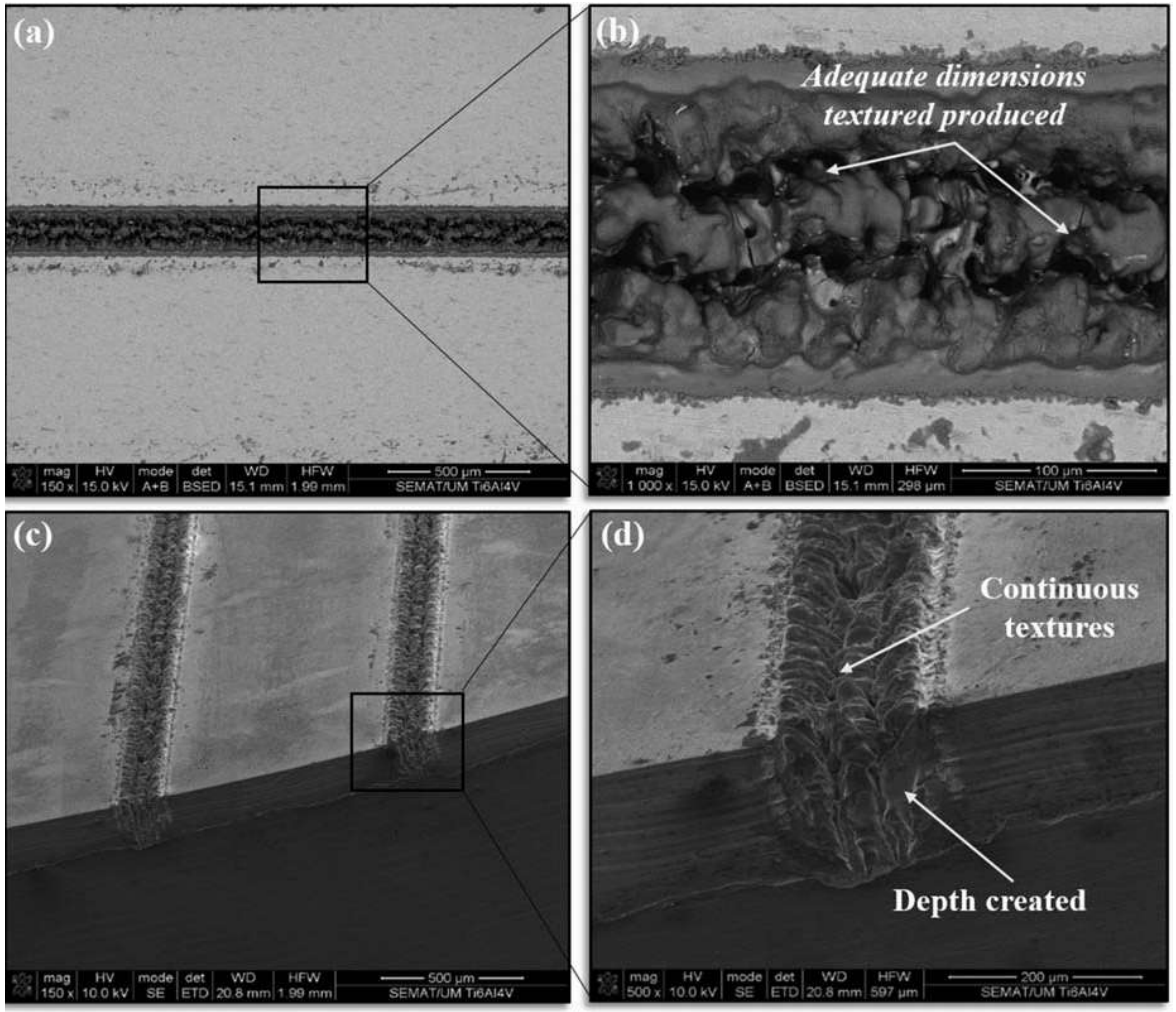


Generation of oriented grooves by means of ns pulsed laser on SS316L
HUVECs directional proliferation evidenced



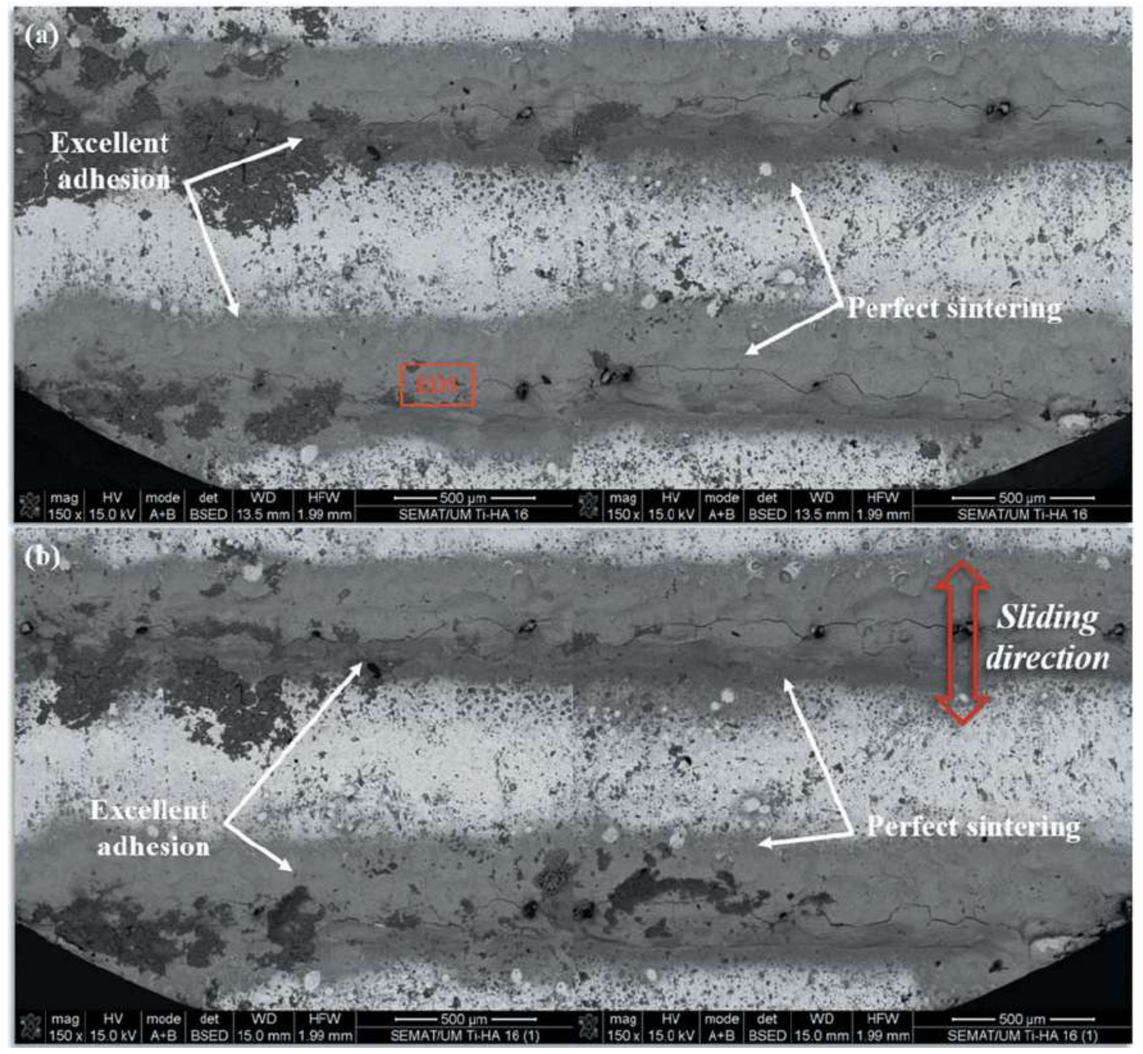


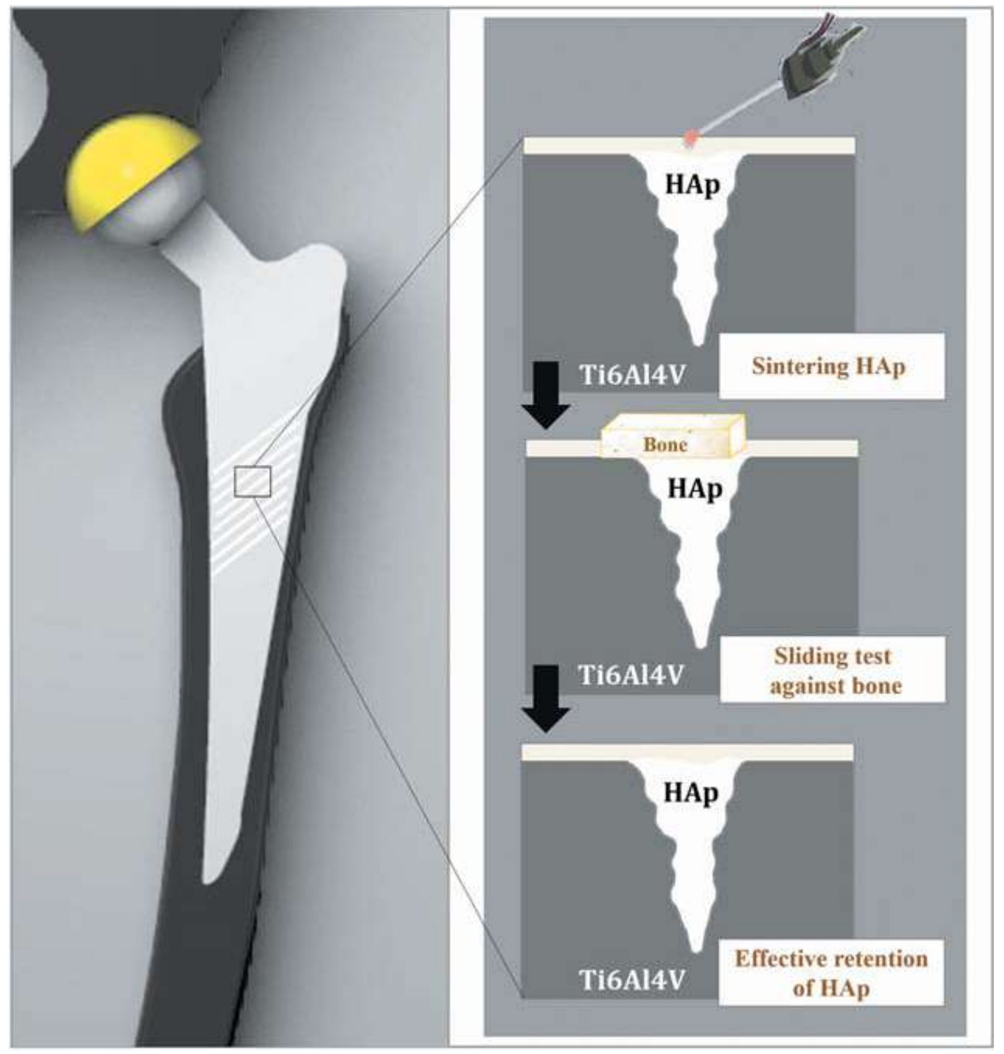
Biomechanical enhancements in implants



D. Faria et al.
Ti6Al4V laser surface preparation and functionalization using hydroxyapatite for biomedical applications
Journal of Biomedical Materials Research Part B (2017)

Use of Nd::YAG to create grooves on hip implants
Fill the grooves with hydroxyapatite and sinterize it by CO2 laser





Biomechanical enhancements in implants

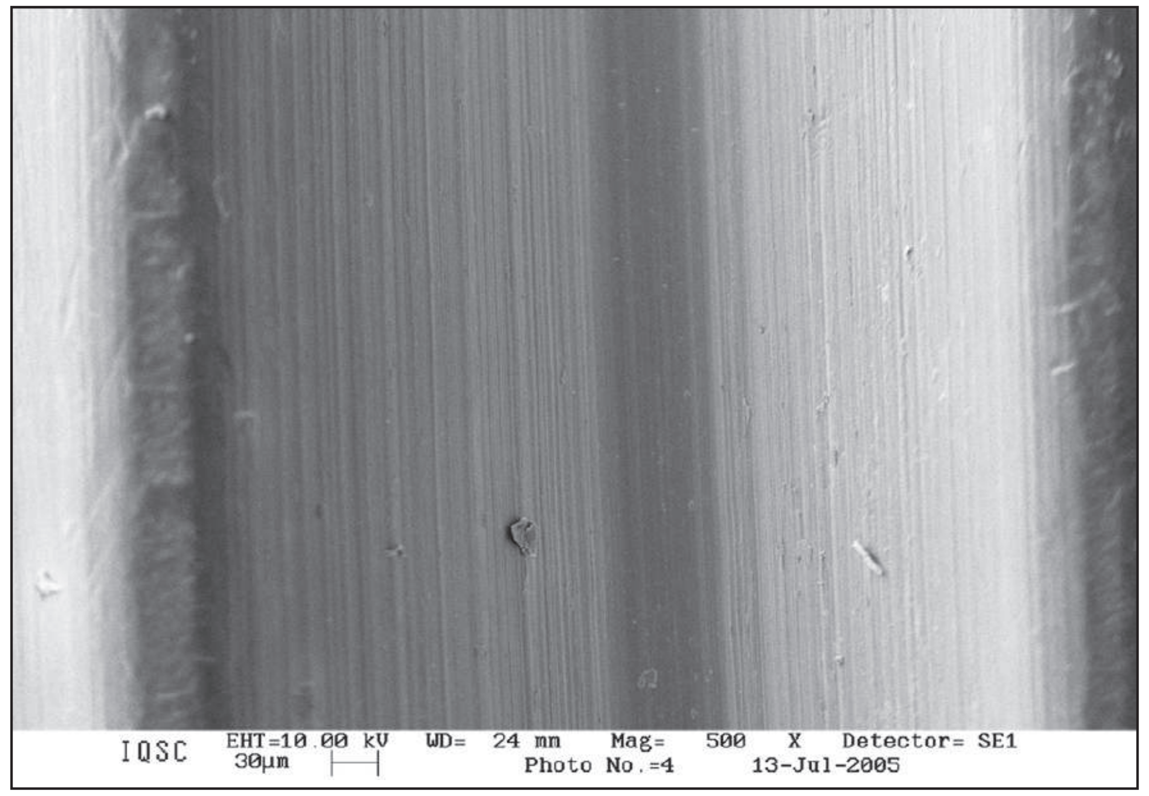


Figure 3 - SEM micrographs of the implants with machined surface, original magnification of 500 X.

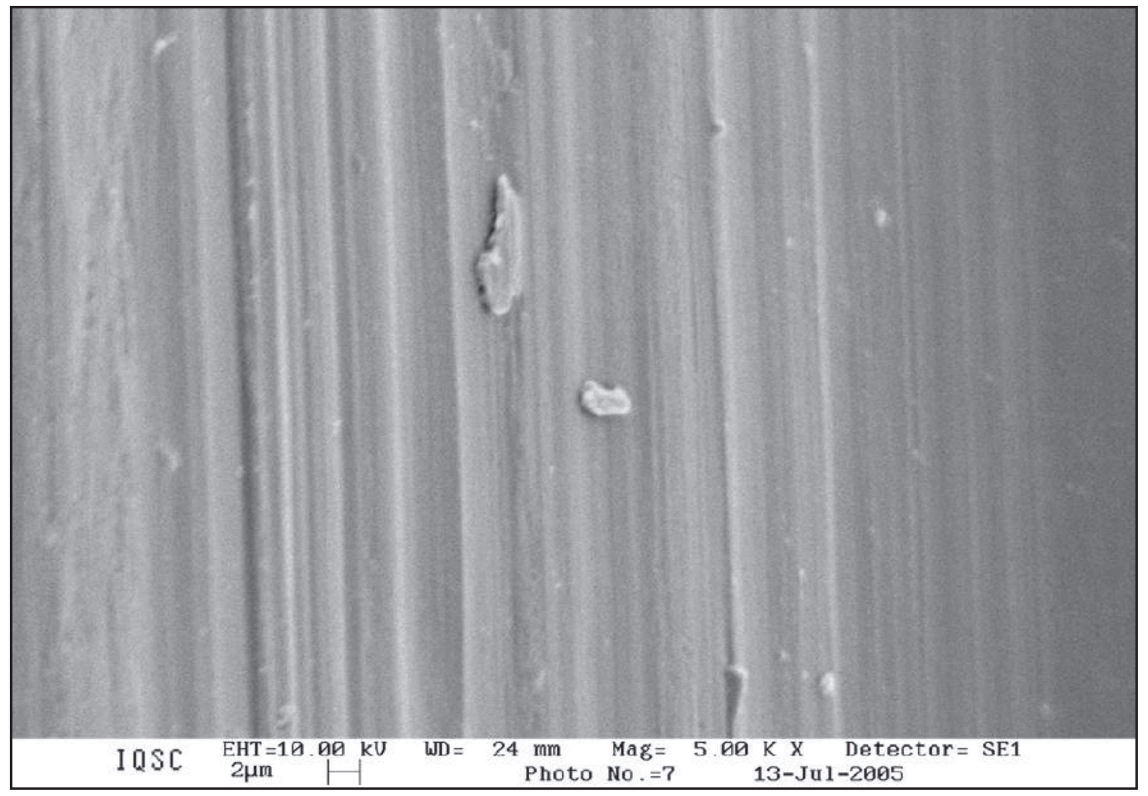


Figure 4 - SEM micrographs of the implants with machined surface, original magnification of 5,000 X.

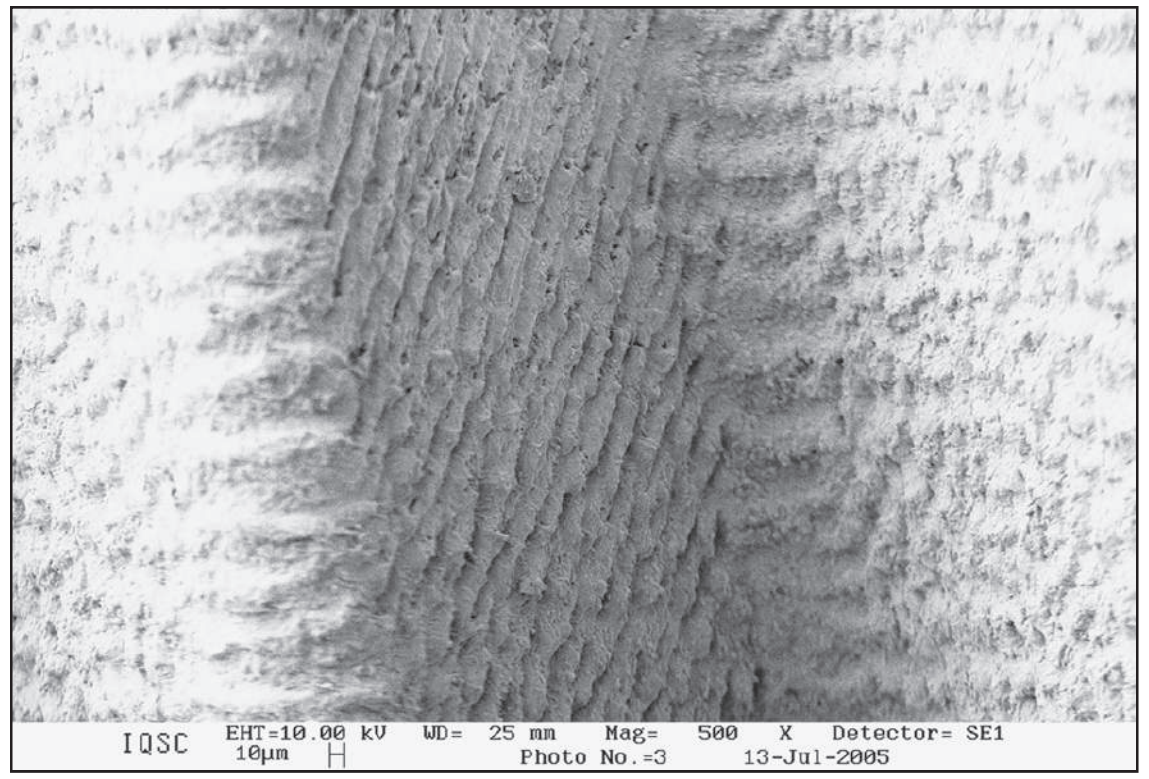


Figure 1 - SEM micrographs of the implants after laser treatment, with original magnification of 500 X.

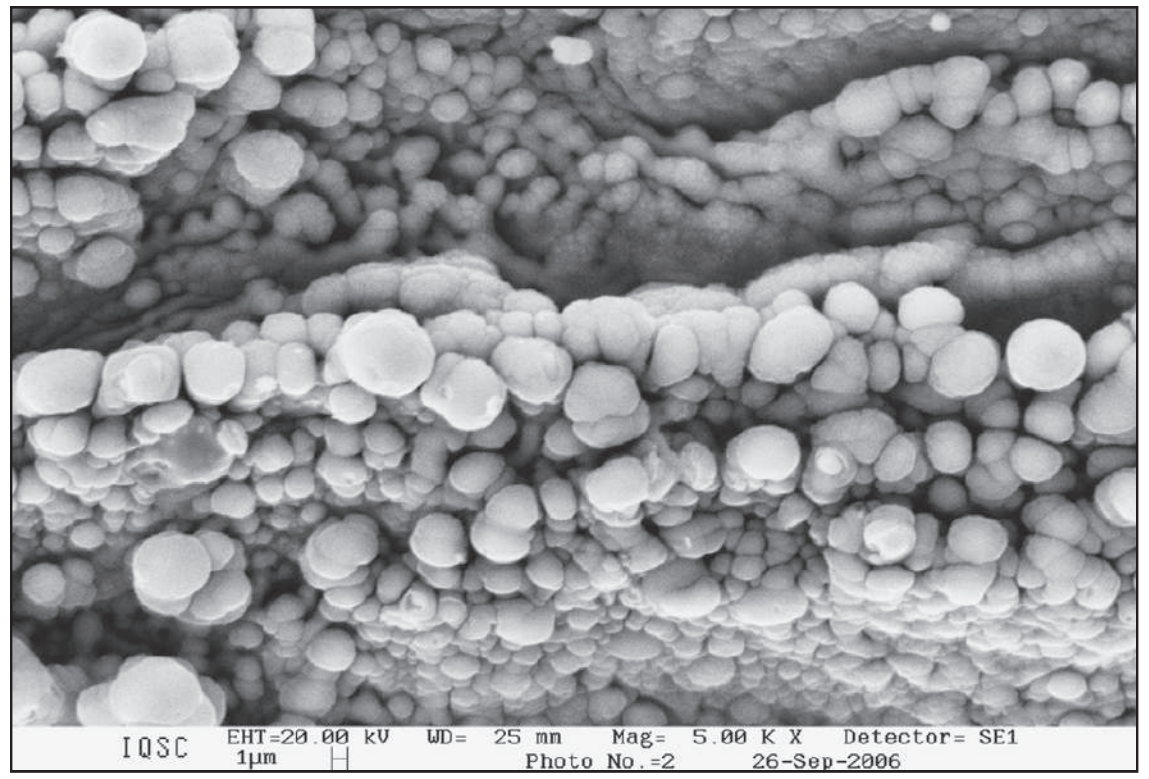
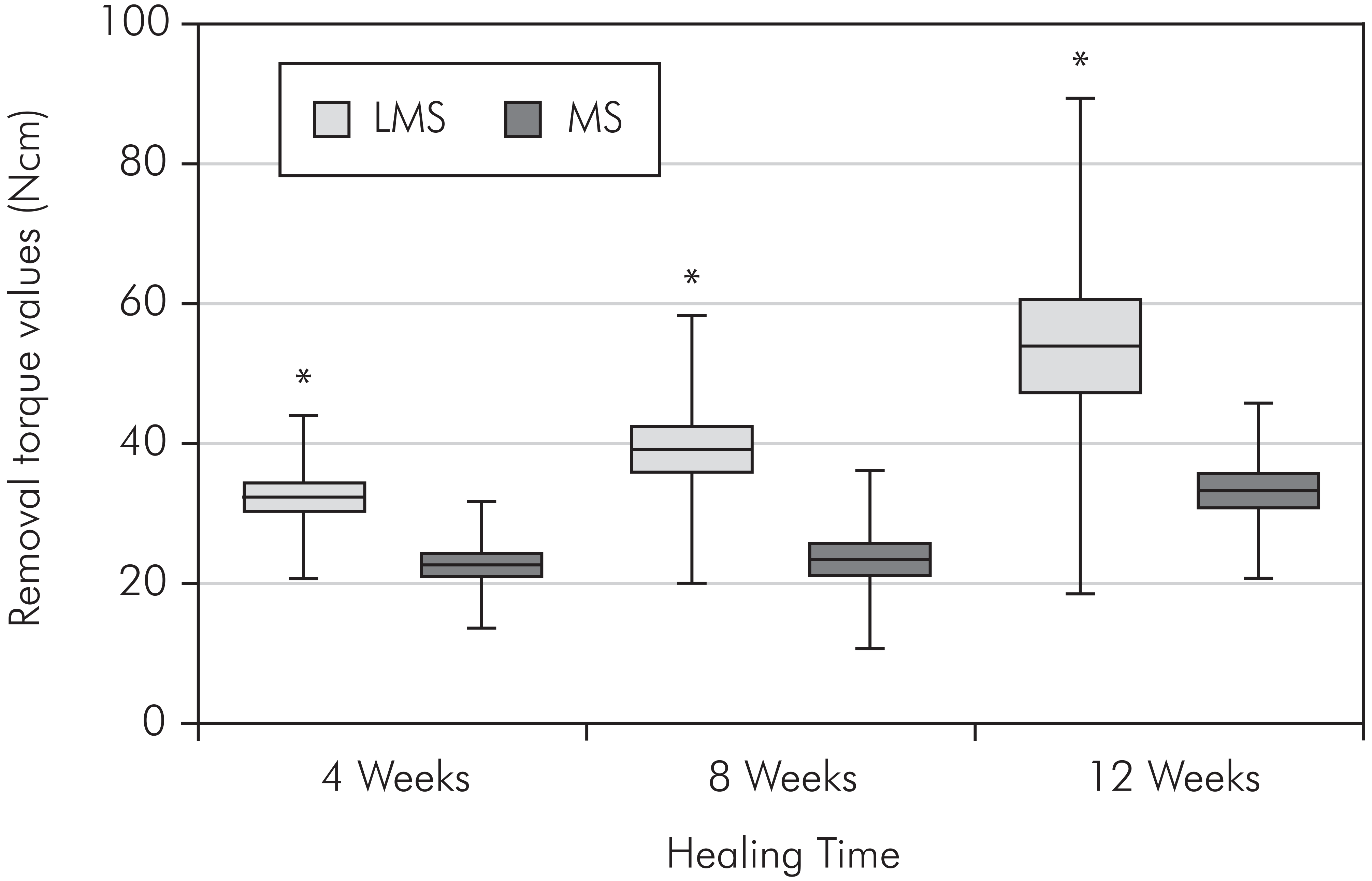


Figure 2 - SEM micrographs of the implants after laser treatment, with original magnification of 5,000 X.

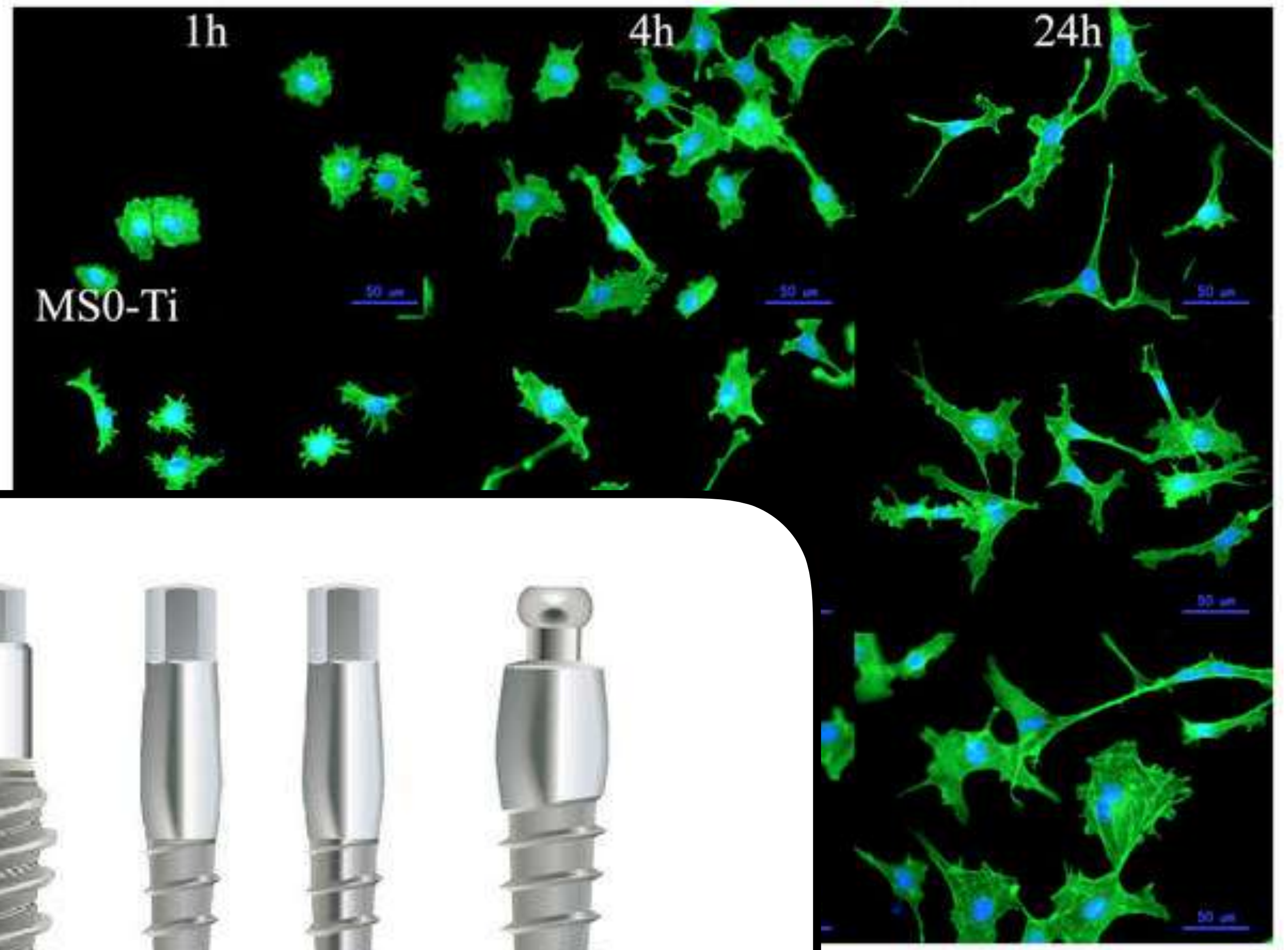
R.S. Faeda et al.
Evaluation of titanium implants with surface modification by laser beam: biomechanical study in rabbit tibias
Implantology (2008)

Removal torque of Ti6Al4V implants with surface machined compared to ns laser treated



Ti/Zr alloys for bio-medical applications

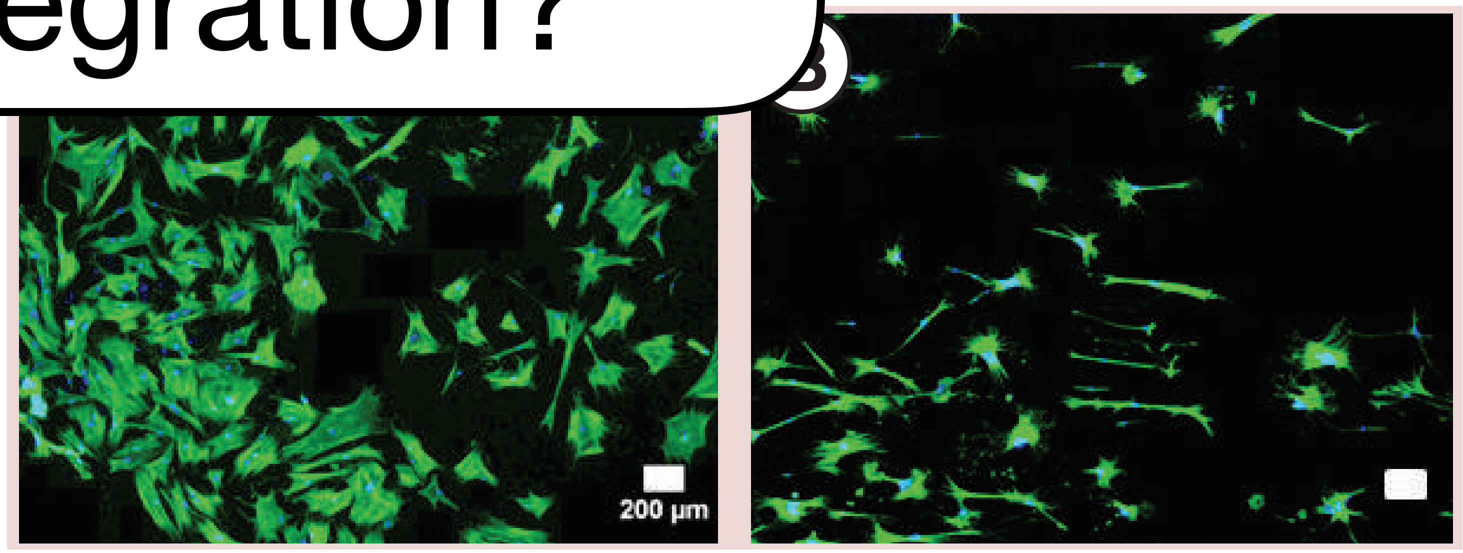
- Collaborative work
  - UNIMORE (IT)
  - Sumy State University, PP Exim
  - Comenius University (SK)
  - IAPS (LV)
  - University of Lisbon (PT)
- Surface nanotexturing to i
and steer the growth of ce
osteoblasts and fibroblast
- 50% of dental implant loss are due to loss of bone support.

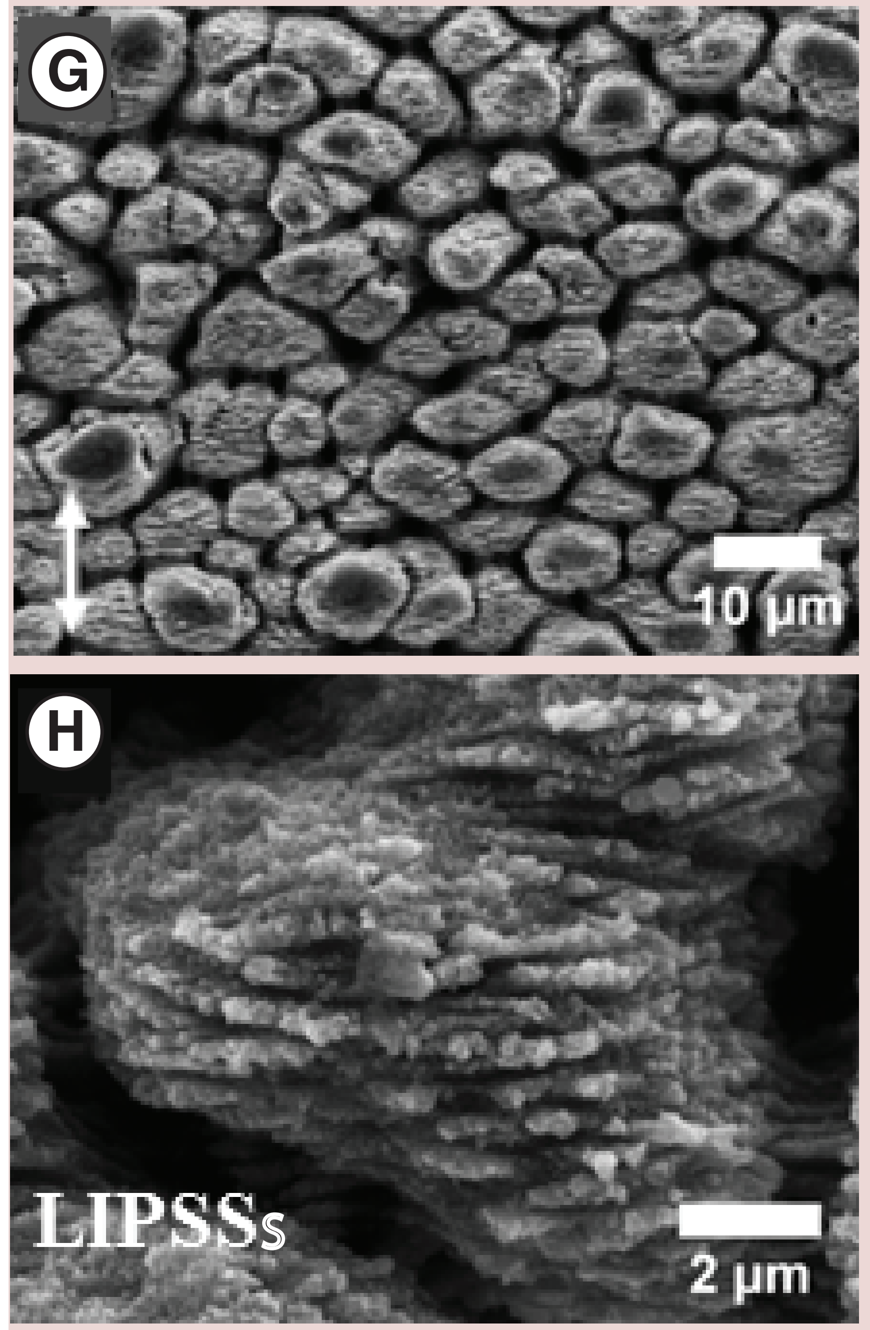


Huang et al. - *The construction of hierarchical structure on Ti substrate with superior osteogenic activity and intrinsic antibacterial capability.* Nature - Scientific Reports 4 - 6172. (2014)

Can LIPSS improve the osteointegration?

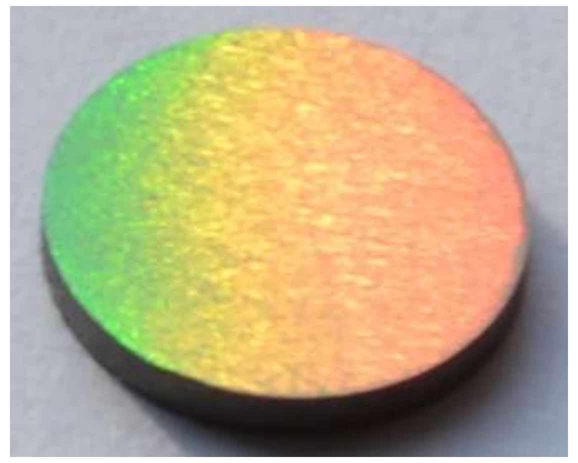
mesenchymal stem cell
laser-textured Ti-6Al-4V
omedicine. (2015)





Esperimental setup

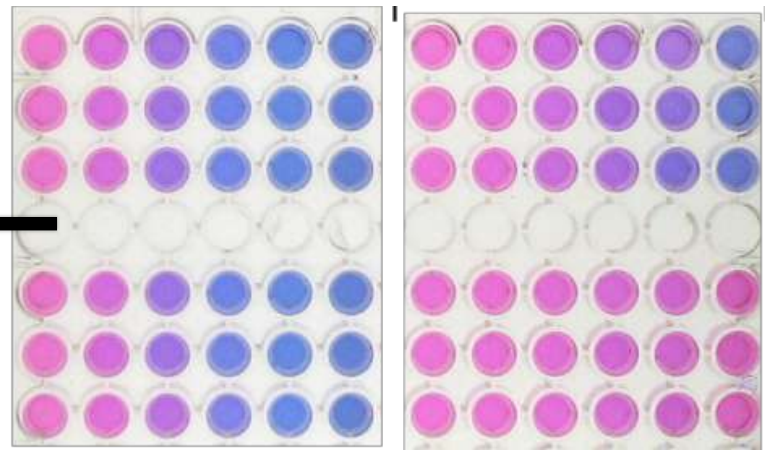
30 samples - 9 mm discs
- Ti6Al4V (commercial grade 1)
- Zr (99.7% purity)

Laser nanopatterning →   ← As is

In Vitro

Dulbecco's Modified Eagle Medium; Fetal Bovine Serum; L-glutamine; Mercaptoethanol
24 h incubation 37 °C

→ Human Dermal Fibroblasts Adult seeding → 

Metabolic Alamar Blue Assay ← 

In Vivo

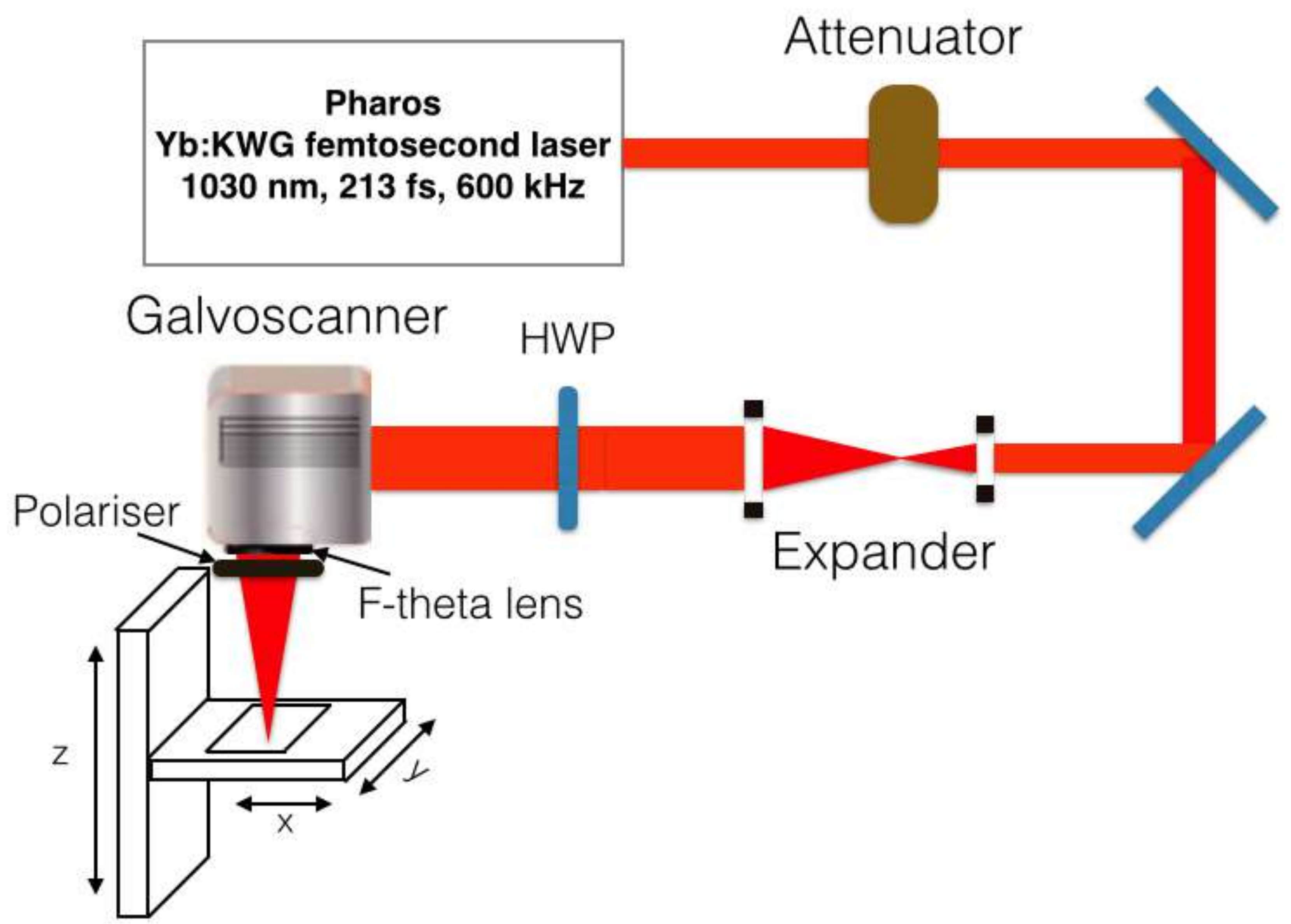
30 lab rats divided in 4 groups

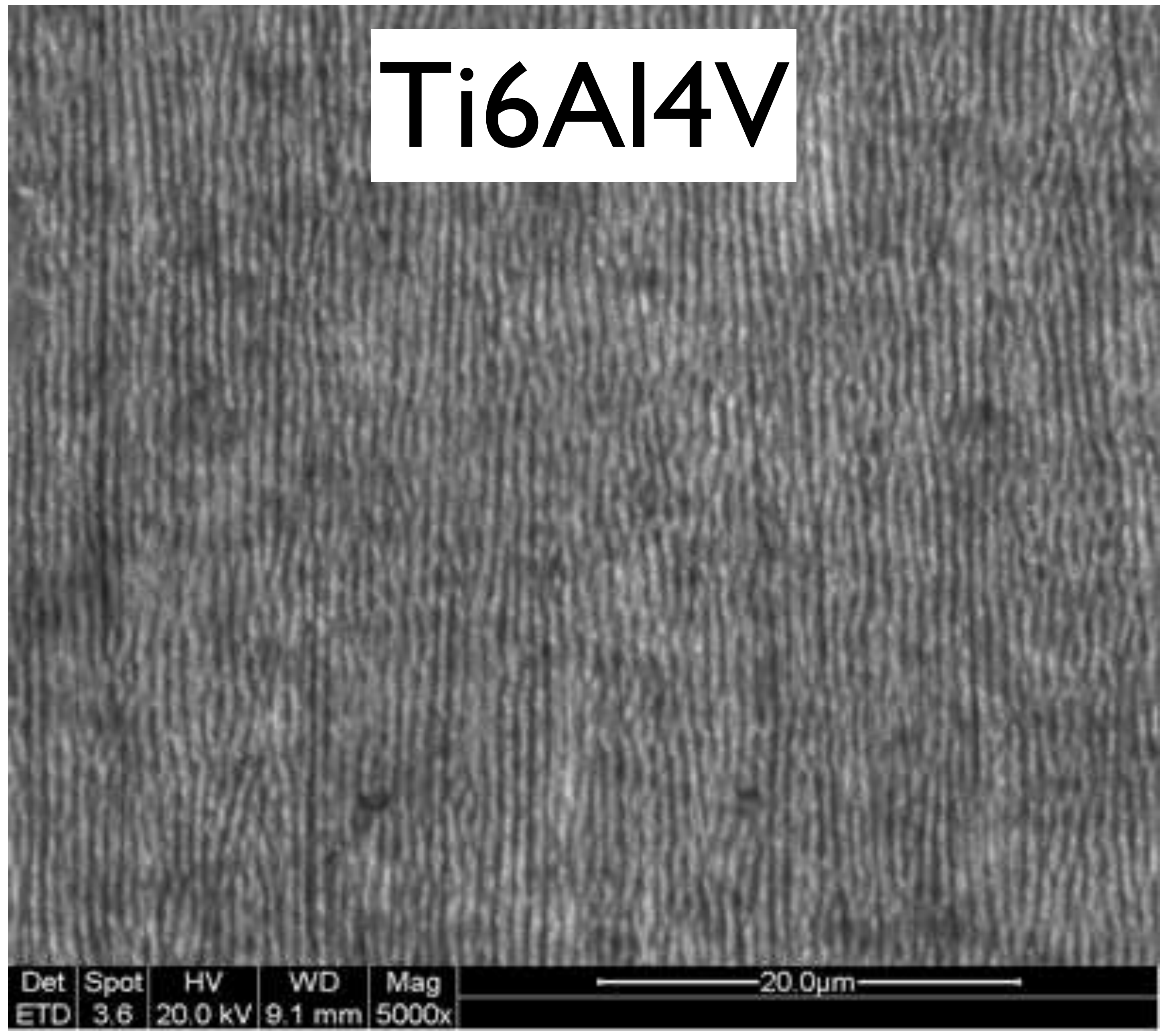
- Ti As is
- Zr As is
- Ti LIPSS
- Zr LIPSS

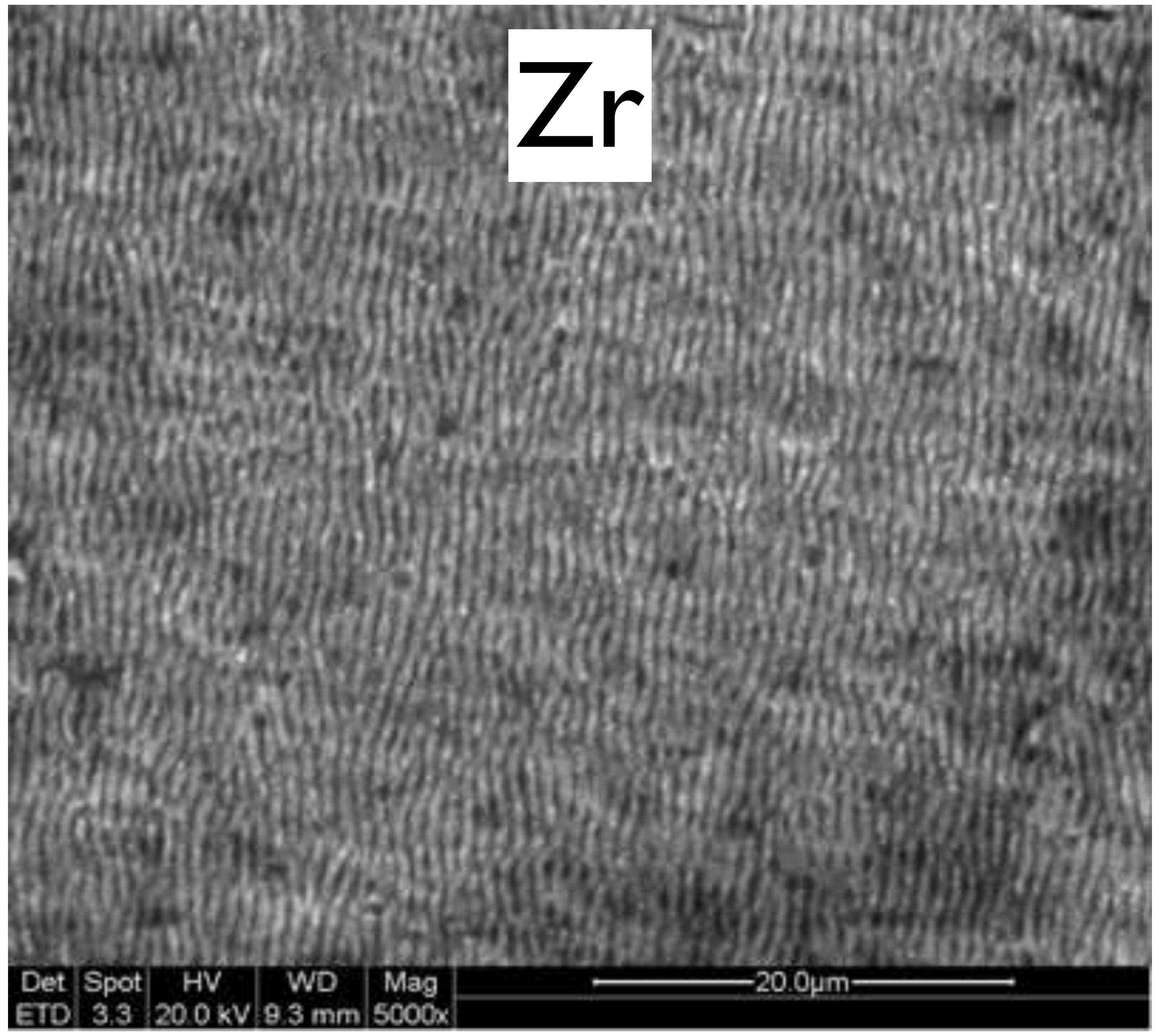
→ SEM Analysis

HR-LIPSS generation

Material	Fluence	Scanstep	Speed	Repetition Rate
	J/cm²	μm	mm/s	kHz
Ti6Al4V	**1.17**	**3**	**3000**	**600**
Zr	**1.33**	**3**	**3000**	**600**



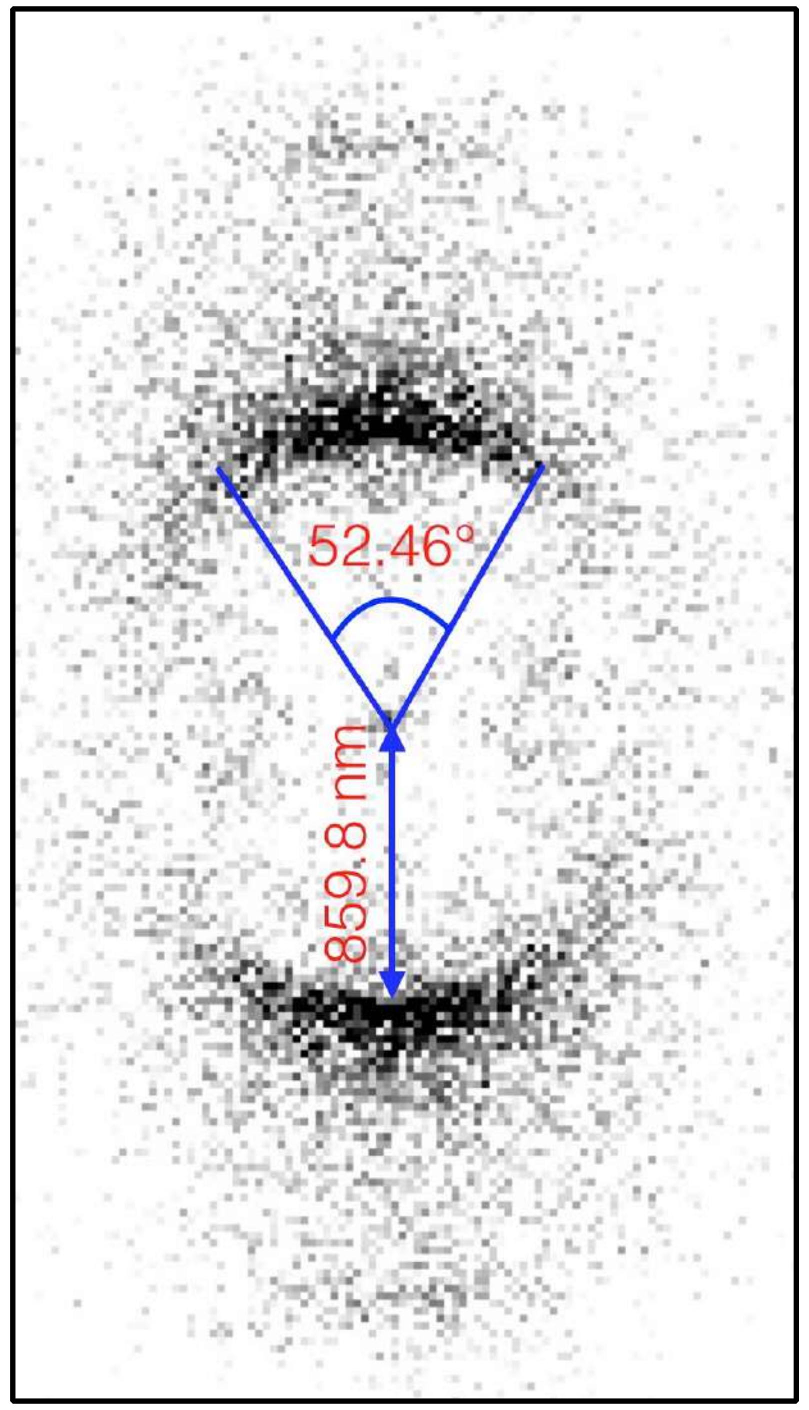


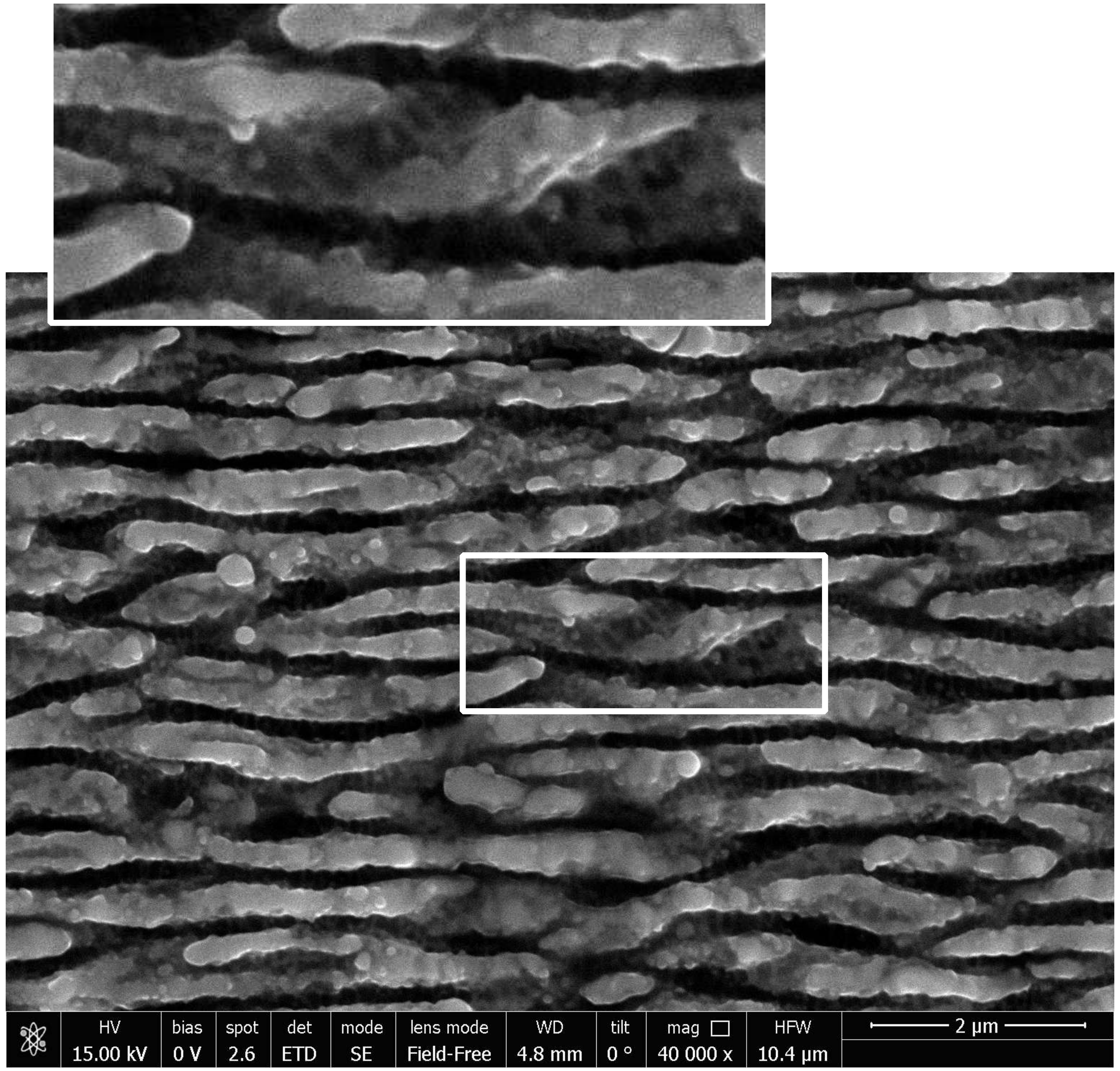


Quasi regular structures obtained on both the materials
Ripples oriented perpendicularly to polarization plane

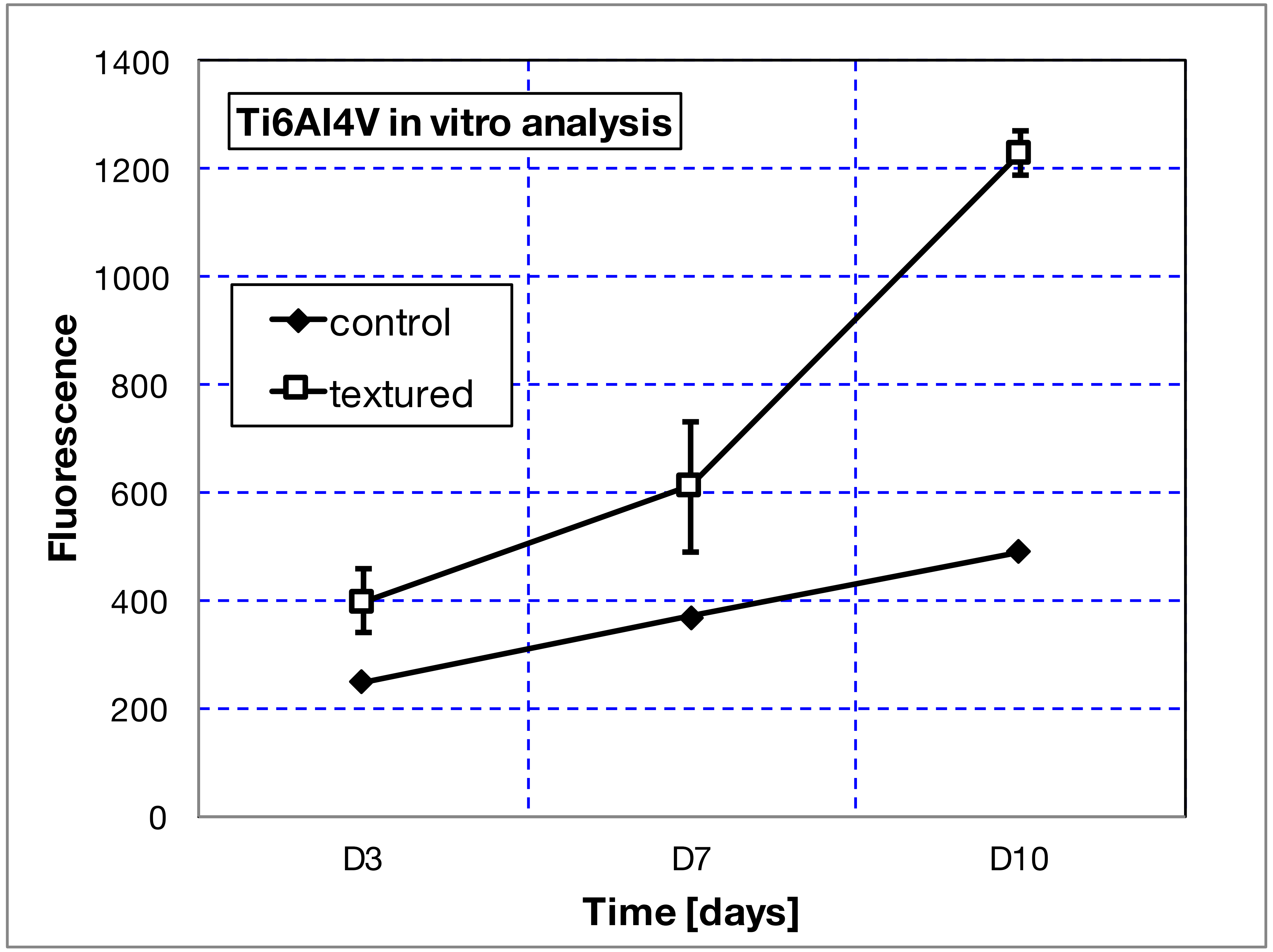
Morphology results

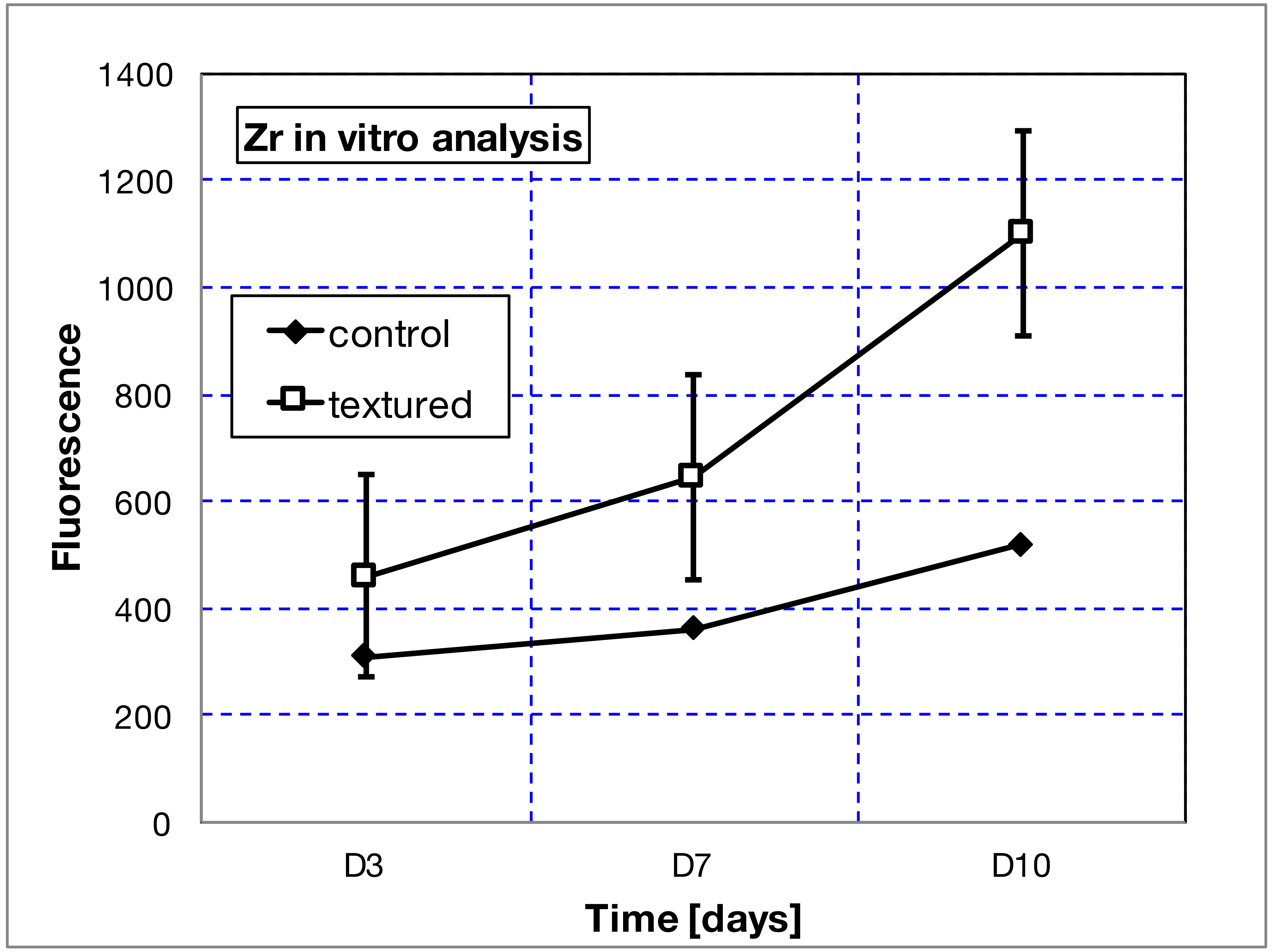
- Periodicity in Zr is about 850 nm.
- For Ti6Al4V periodicity is about 650 nm.
- The presence of High Spatial Frequency LIPPS (HSFL) is observed.
- Surfaces were characterized by means of 2D FFT.





Cells viability: in-vitro results analysis

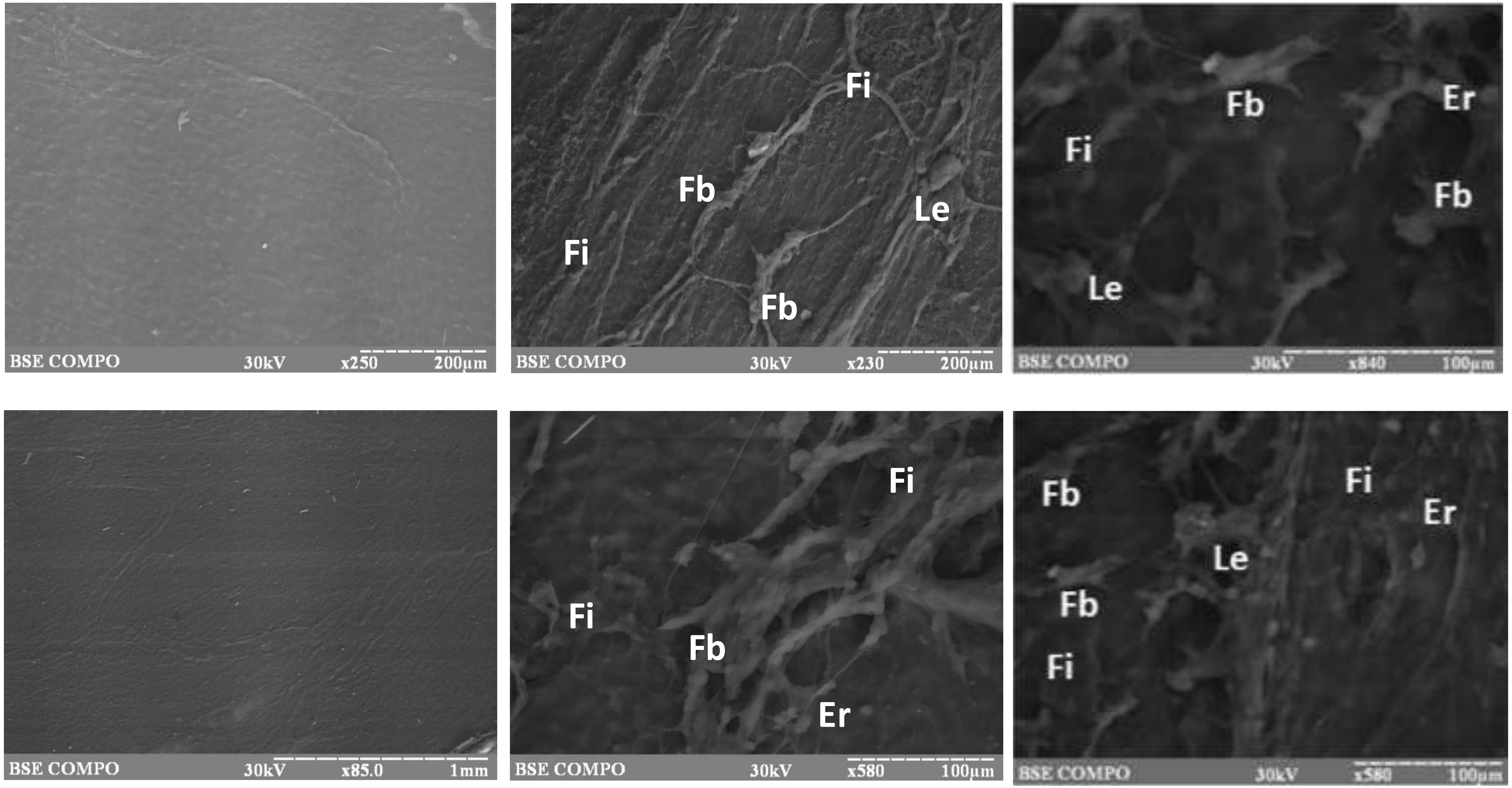




Cells viability: in vivo results analysis

Ti6Al4V

Zr



Connective fibres (Fi)
Erythrocytes (Er)
Leucocytes (Le)
Fibroblasts (Fb)

Ok, all is fine with flat surfaces for lab testing but what about real complex geometries?

Manufacturing and ns-laser texturing of jaw model

- Stainless steel model
- 5 mechanical axis + 3 optical axis
- 20 W, 180 ns, 80 kHz laser

Conclusions

- Laser surface texturing is a simple and robust method to treat surfaces changing both morphology and surface chemistry.
- In many cases LIPSS and/or microtexturing treatments can be conducted in air environment.
- In-vivo and In-vitro results shown a significative improvements in cells viability.
- Surface modifications maintain bio-compatibility of the material: no new clinical trials are required.

UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

Department of Sciences and Methods for Engineering

Laser surface processing for biomedical applications

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VI International Conference «TOPICAL ISSUES OF THEORETICAL AND CLINICAL MEDICINE
SUMY - 18/10/2018