UNIVERSITÀ
DEGLI STUDI DI BARI
ALDO MORO

DIPARTIMENTO INTERATENEO DI FISICA “M. MERLIN"
Dottorato di ricerca in FISICA – Ciclo XXXI
Settore Scientico Disciplinare: FIS/01

Laser micromachining with bursts of ultrashort pulses

Dottorando: Giuseppe Giannuzzi

Tutors: Dott. A. Ancona,
Prof. V. Spagnolo
Coordinatore: Ch.mo Prof. G. Iaselli
Progetto di ricerca: Microlavolazioni con burst di impulsi laser ultrabrevi

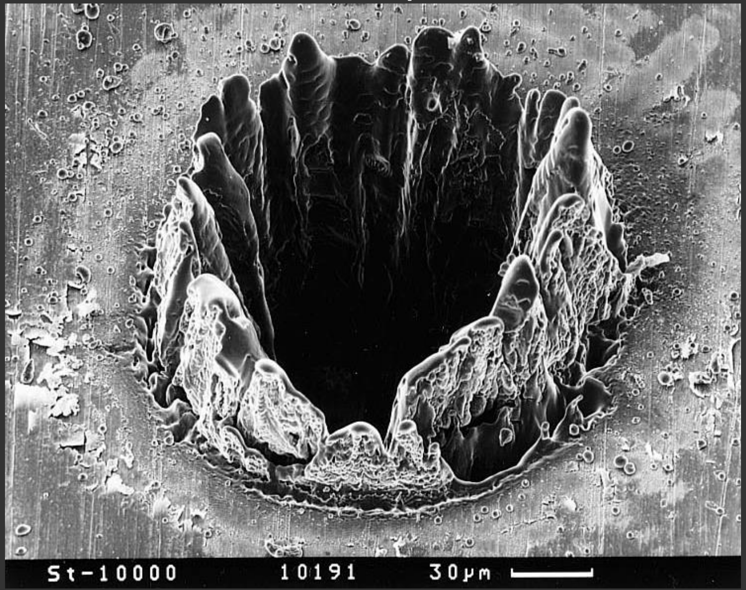
Bari, 9 Novembre 2018

Outline

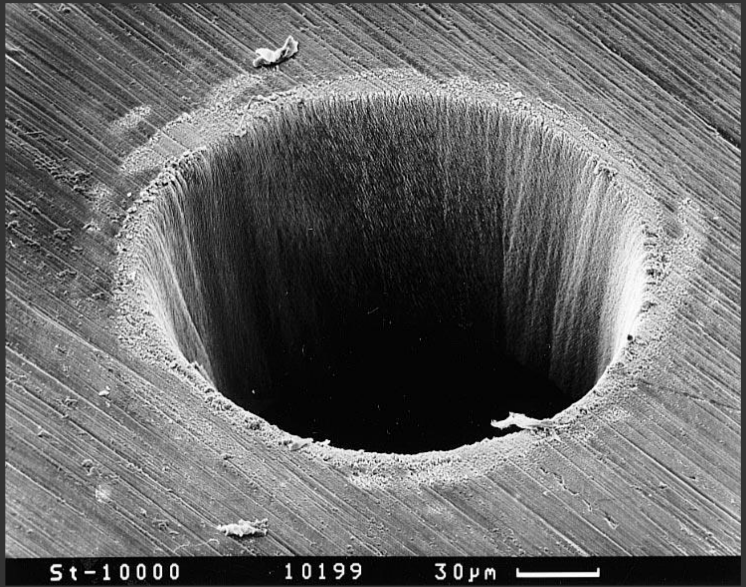
- Motivation
- Bursts of ultrashort pulses
- Experimental set-up
- Results:
  - Ablation threshold fluence
  - Ablation process
  - Surface texturing
- Conclusions

Why ultrashort pulses?

Hole drilled in a 100 µm thick steel foil



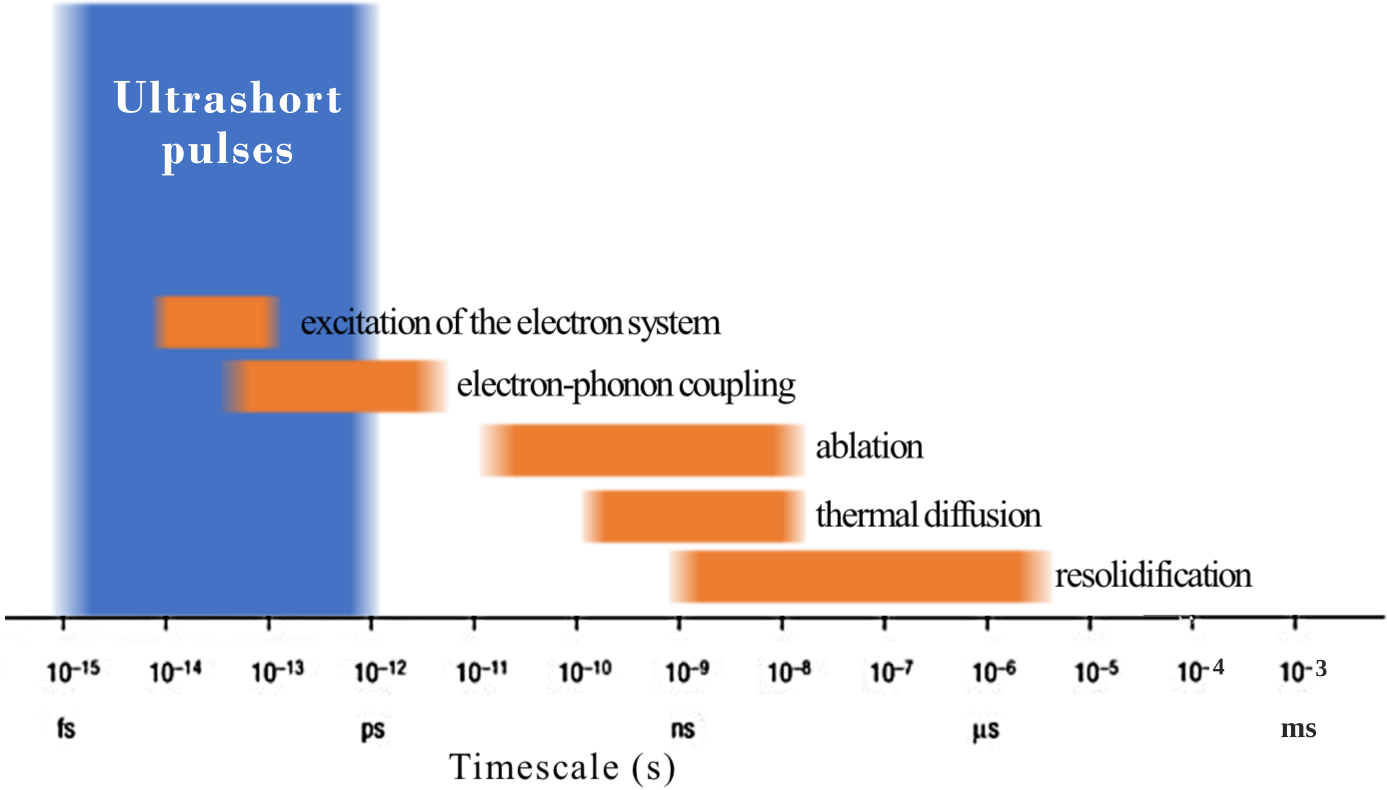
$\tau = 3.3\ ns$
$E = 1\ mJ$
$F = 4.2\ J/cm^2$
$\lambda = 780\ nm$



$\tau = 200\ fs$
$E = 120\ \mu J$
$F = 0.5\ J/cm^2$
$\lambda = 780\ nm$

B. N. Chickov, et. al., Applied Physics A, Mat. Sci. Proc., 63, 109-115 (1996).

Timescales of ultrashort pulse interaction with metals



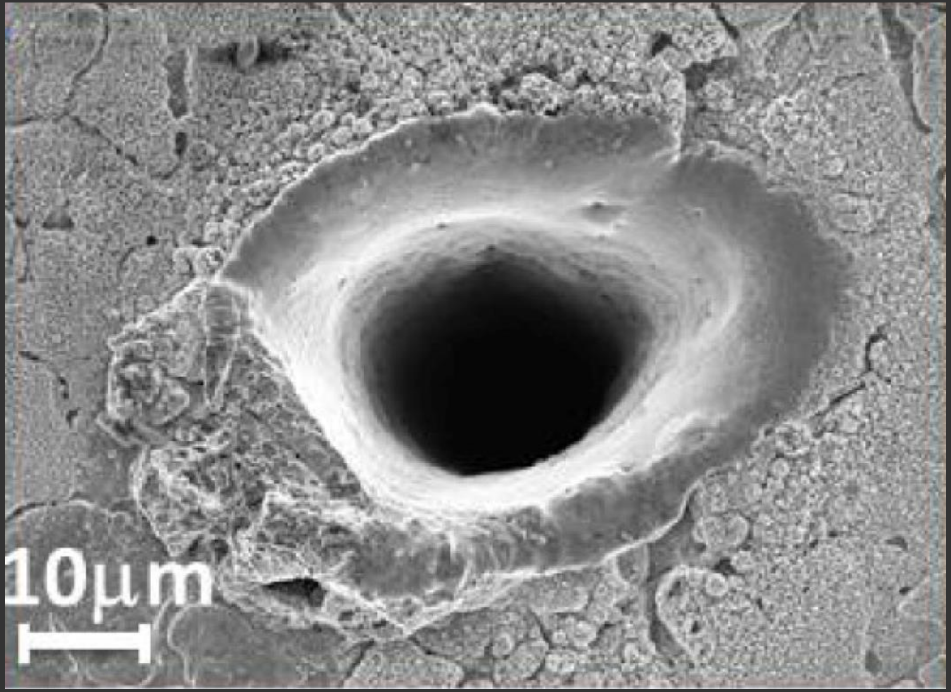
Adapted from: S. Sundaram, E. Mazur, Nat. Mater. 1 (2003) 217–224.

MHz regime

Heat accumulation

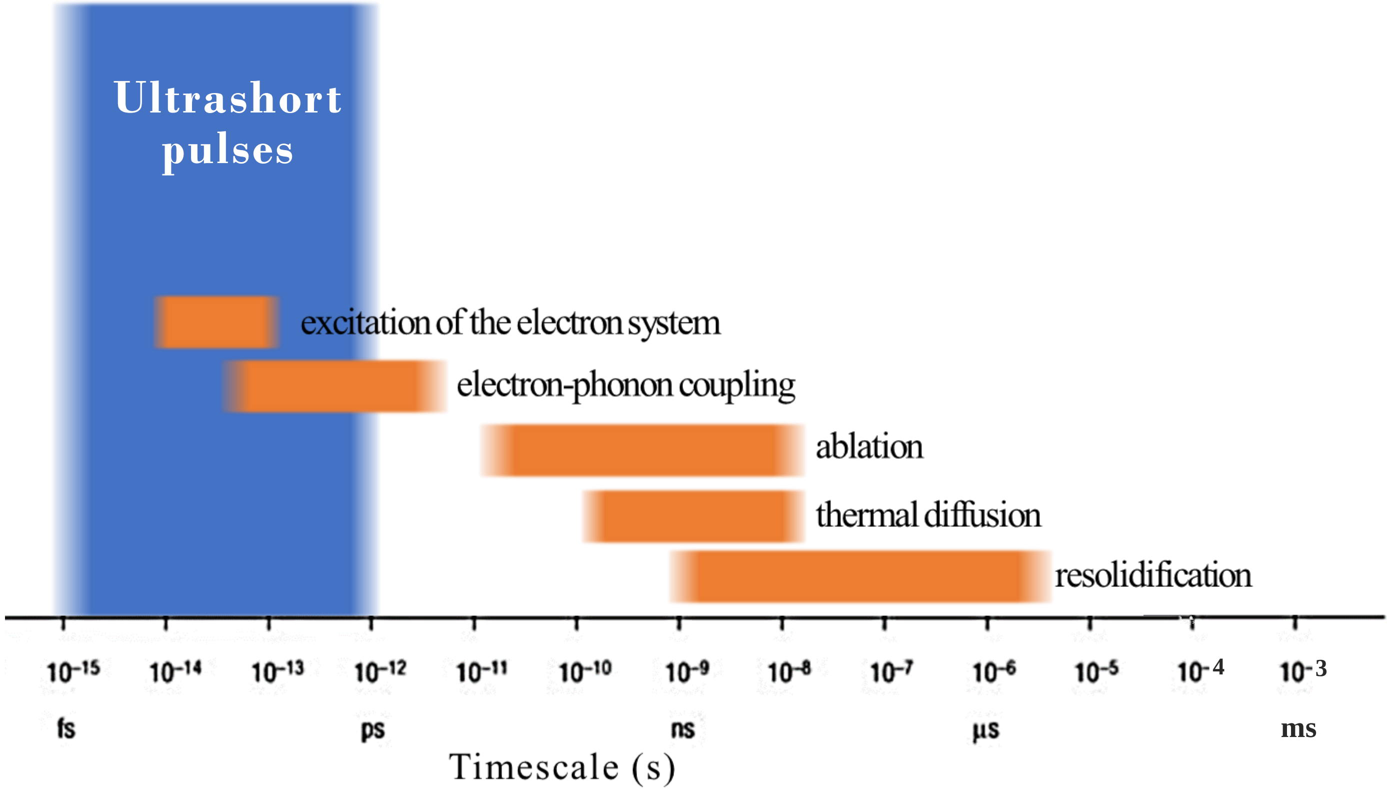
$\tau = 650\ fs;\ E = 10\ \mu J$

$1\ MHz$



F. Di Niso et al., Opt. Express 22 (10), 12200–12210 (2014).

Timescales of ultrashort pulse interaction with metals



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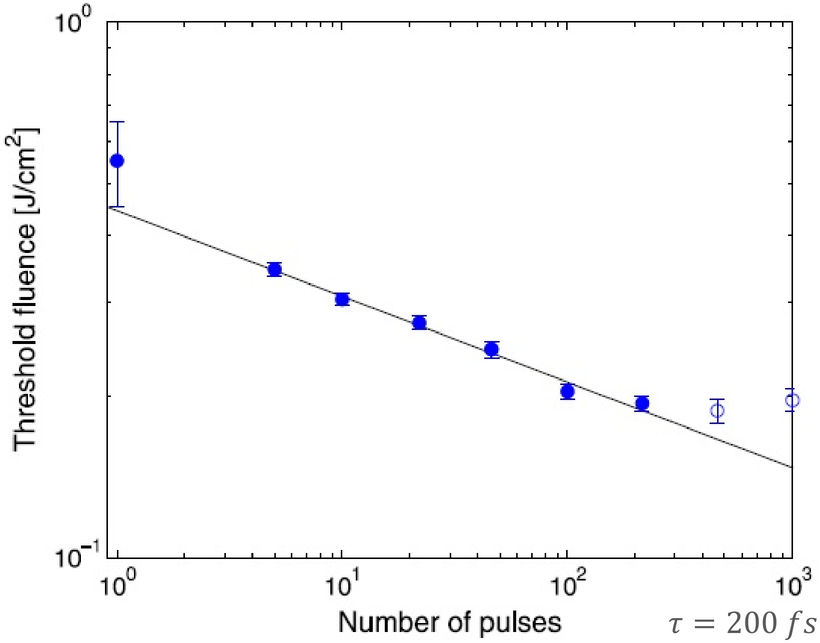
PhD student: Giuseppe Giannuzzi

Incubation effect



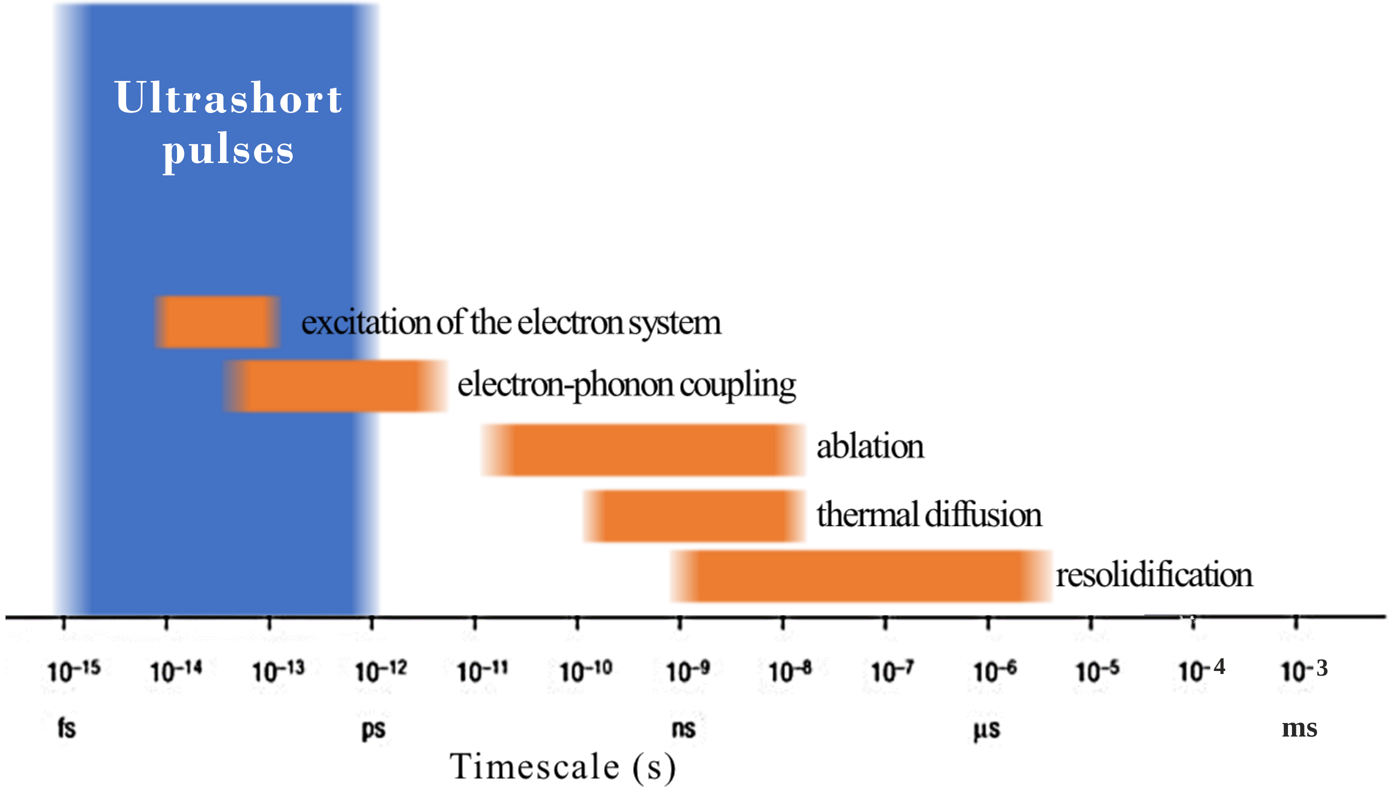
$\tau = 200\ fs$

$$\Phi_{th}(N) = \Phi_{th}(1)\ N^{S-1}$$

$\Phi_{th}(1)$ threshold fluence for N pulses
$\Phi_{th}(N)$ threshold fluence for a single pulse
S incubation coefficient

J. Byskov-Nielsen et al., Appl. Phys. A, 101, 97-101 (2010).

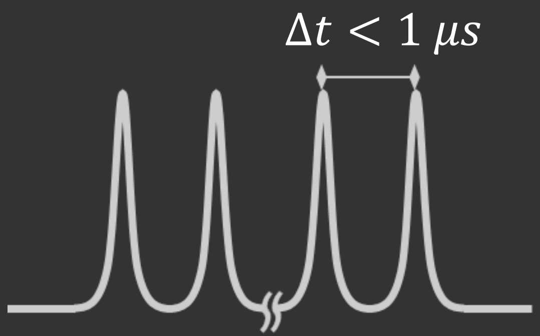
Timescales of ultrashort pulse interaction with metals



Adapted from: S. Sundaram, E. Mazur, Nat. Mater. 1 (2003) 217–224.

PhD student: Giuseppe Giannuzzi

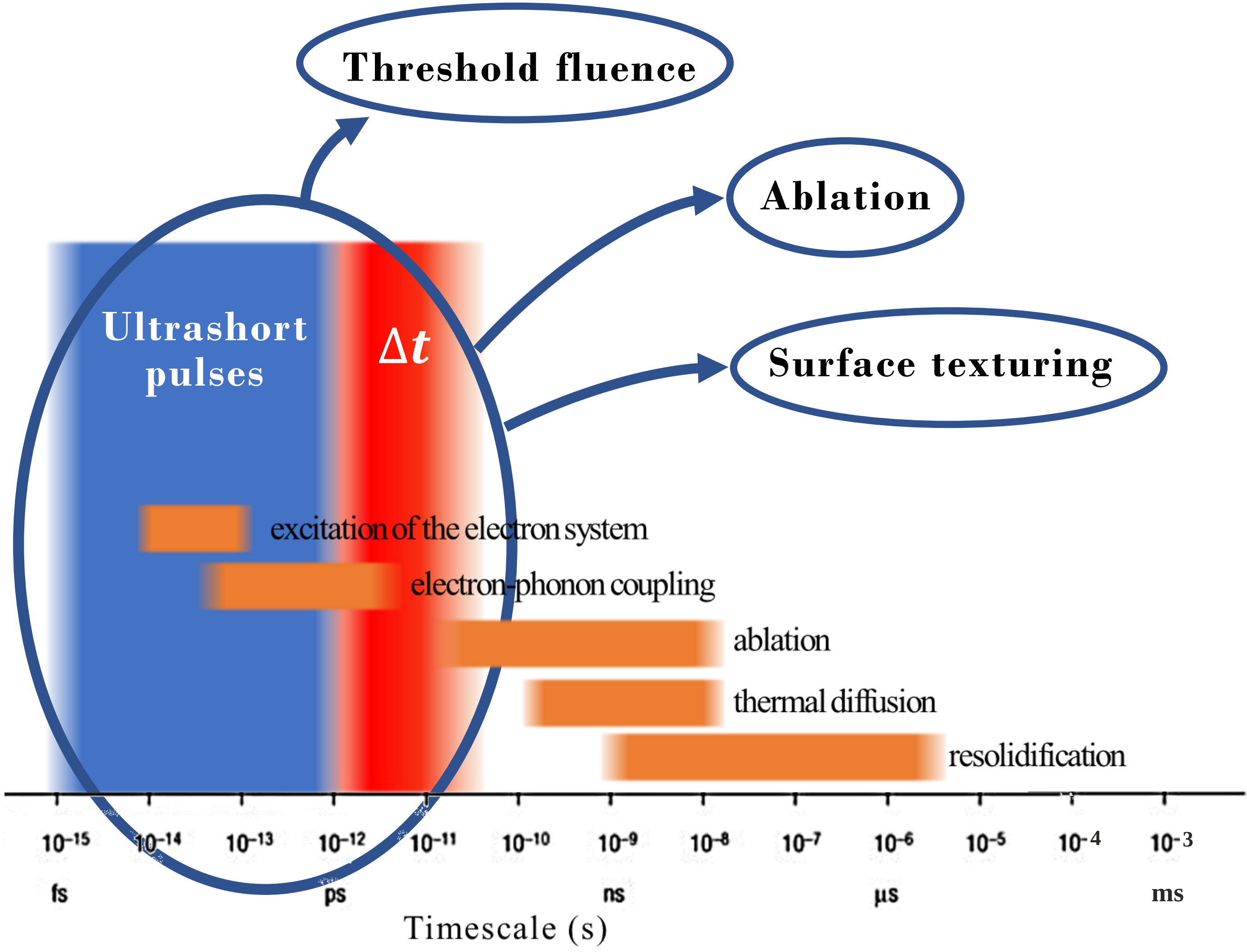
Bursts of ultrashort pulses



Δt time delay

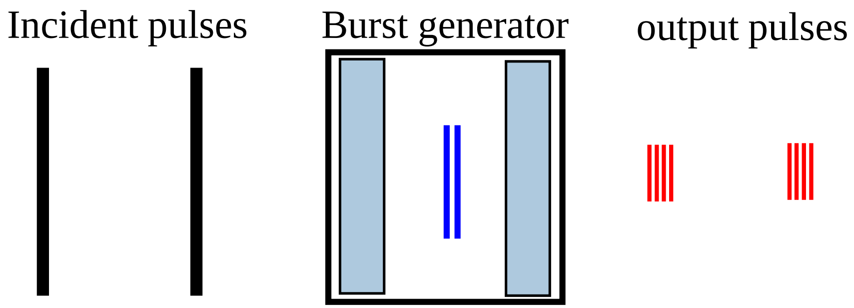
n number of pulses

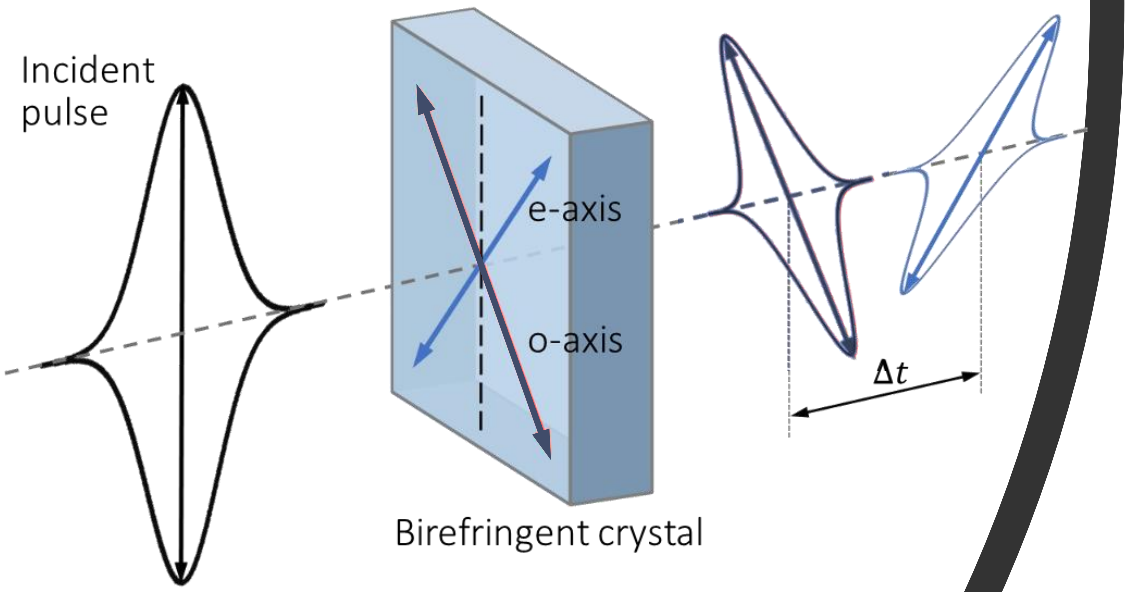
Timescales of ultrashort pulse interaction with metals



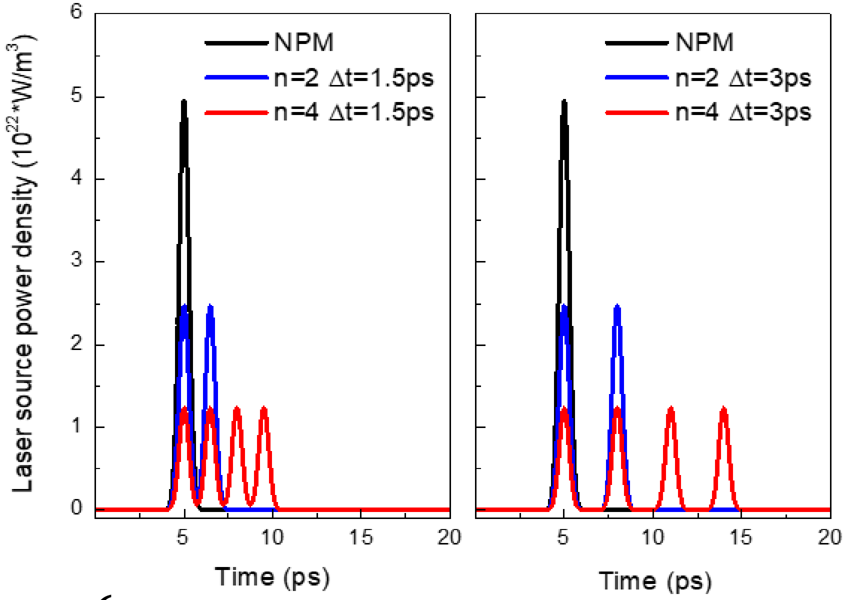
Adapted from: S. Sundaram, E. Mazur, Nat. Mater. 1 (2003) 217–224.

Bursts generation





Numerical simulations of the TTM with burst of pulses



Two Temperature Model

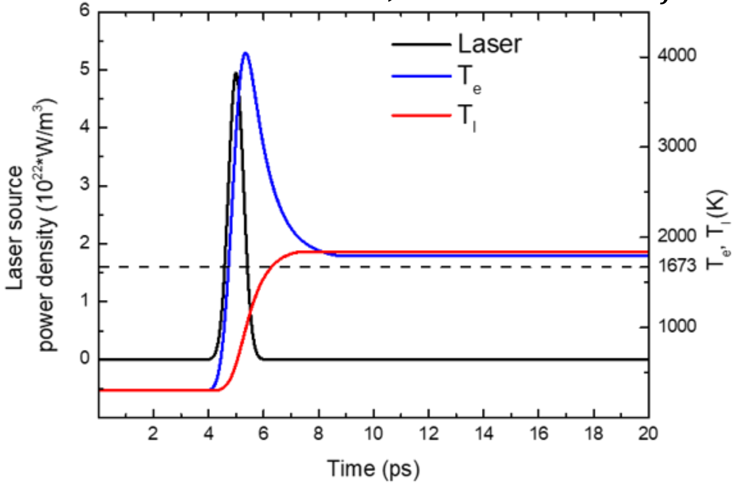
$$\begin{cases} c_e \dfrac{\partial T_e}{\partial t} = \nabla(\kappa_e \nabla T_e) - \mathrm{G}\,(T_e - T_l) + Q \\ c_l \dfrac{\partial T_l}{\partial t} = \nabla(\kappa_l \nabla T_l) - \mathrm{G}\,(T_e - T_l) \end{cases}$$

$T_e = T_e(z,t), T_l = T_l(z,t)$	electron and lattice temperature
$C_e = C_e(T_e), C_l$	electron and lattice heat capacity
$\kappa_e = \kappa_e(T_e), \kappa_l$	electron and lattice thermal conductivity
$\mathrm{G} = \mathrm{G}(T_e)$	electron–phonon coupling factor
Q	heat source

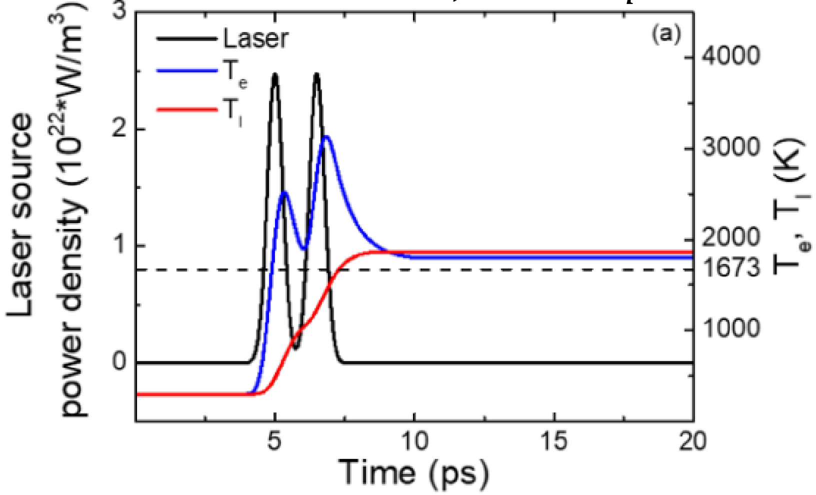
PhD student: Giuseppe Giannuzzi

Numerical simulations of the TTM with burst of pulses

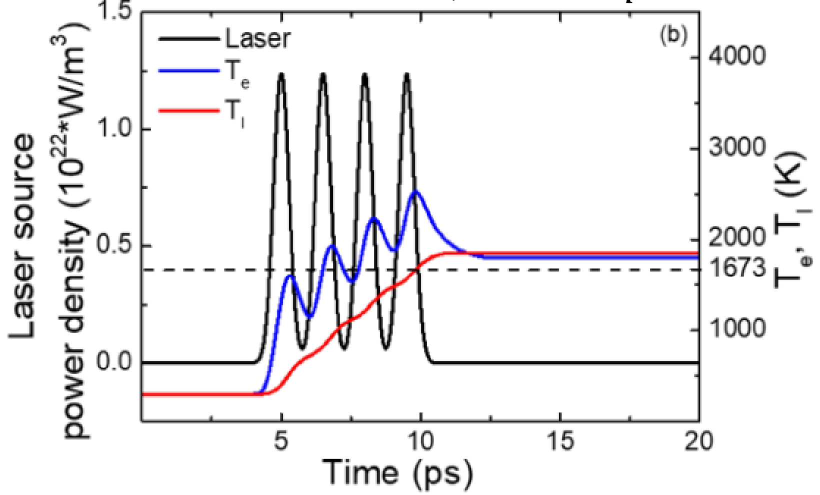
Normal Pulse Mode, $FWHM = 650\ fs$



Burst Mode: $n = 2$, $\Delta t = 1.5\ ps$



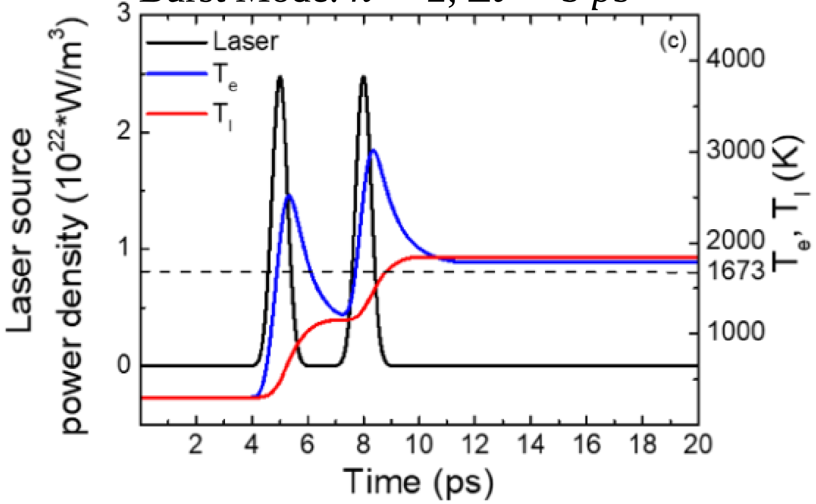
Burst Mode: $n = 4$, $\Delta t = 1.5\ ps$



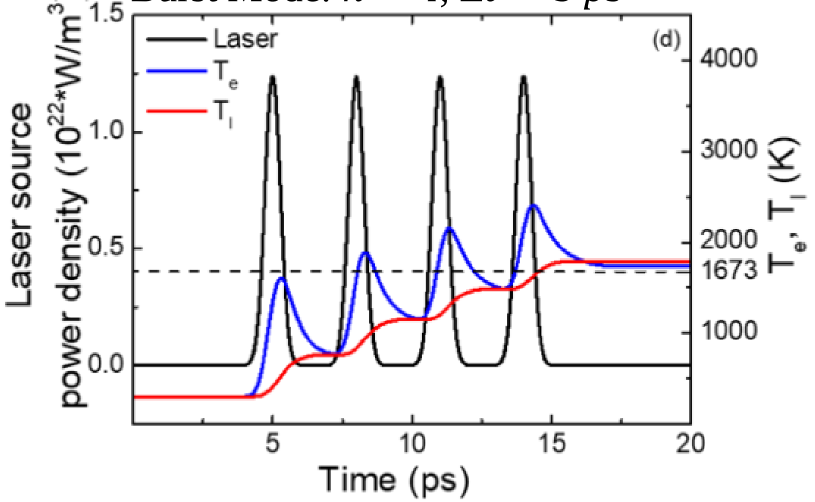
Normalized energy for reaching melting

	$\Delta t = 1.5\ ps$	$\Delta t = 3\ ps$
NPM	100%	
$n = 2$	99.9%	100%
$n = 4$	75.0%	99.1%

Burst Mode: $n = 2$, $\Delta t = 3\ ps$



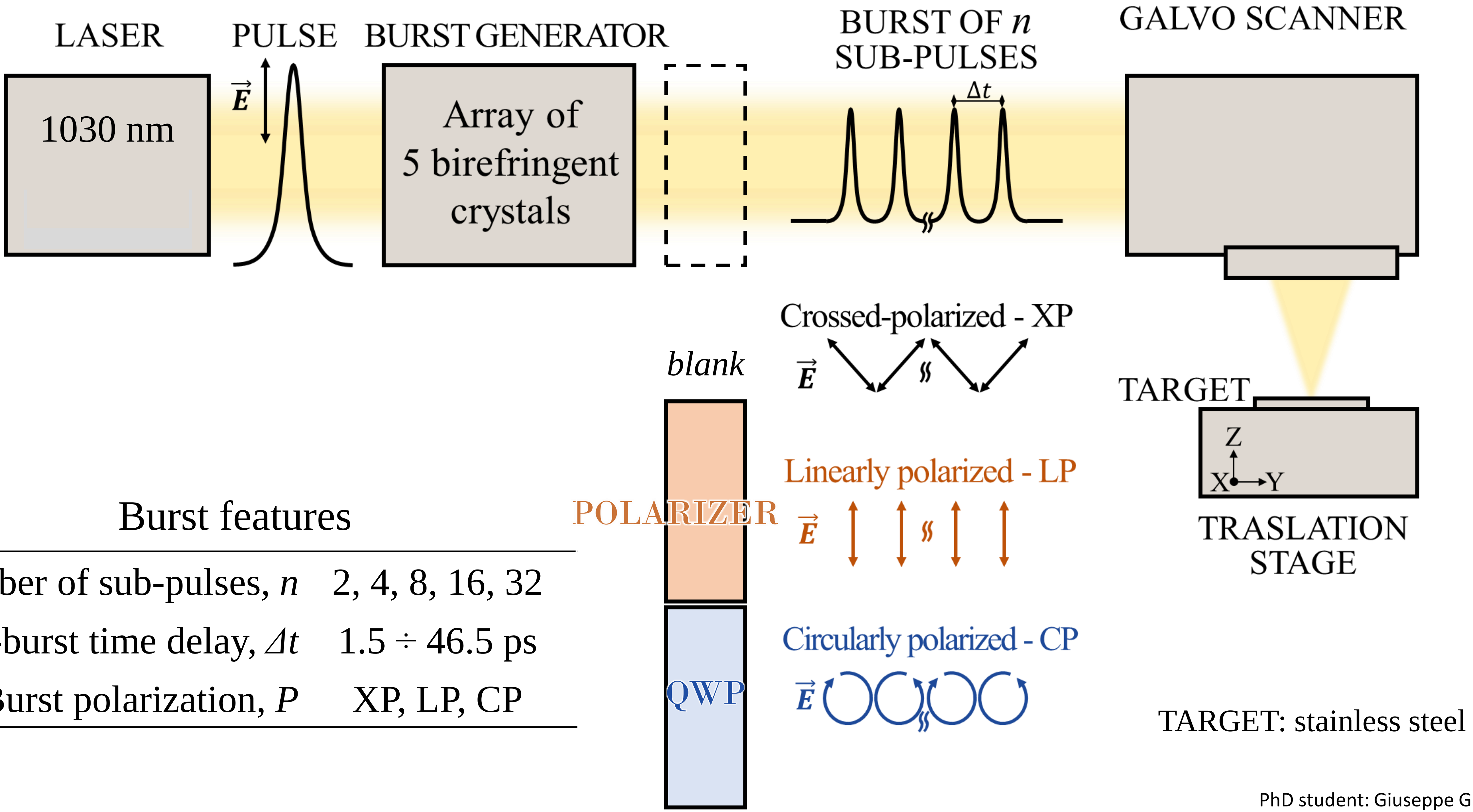
Burst Mode: $n = 4$, $\Delta t = 3\ ps$



More efficient energy transfer with bursts of ultrashort pulses

PhD student: Giuseppe Giannuzzi

Experimental set-up



LASER

1030 nm

PULSE

$\vec{E}$

BURST GENERATOR

Array of 5 birefringent crystals

BURST OF n SUB-PULSES

Δt

GALVO SCANNER

blank

POLARIZER

QWP

Crossed-polarized - XP

$\vec{E}$

Linearly polarized - LP

$\vec{E}$

Circularly polarized - CP

$\vec{E}$

TARGET

Z

X

Y

TRASLATION STAGE

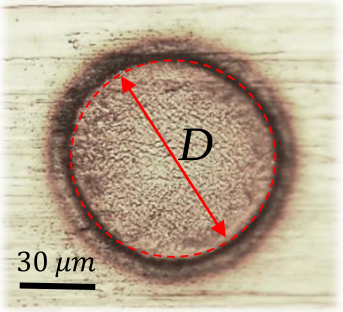
TARGET: stainless steel

Burst features

Number of sub-pulses, *n*	2, 4, 8, 16, 32
Intra-burst time delay, *Δt*	1.5 ÷ 46.5 ps
Burst polarization, *P*	XP, LP, CP

Ablation threshold fluence Φ_{th} in NPM and BM

Ablation crater



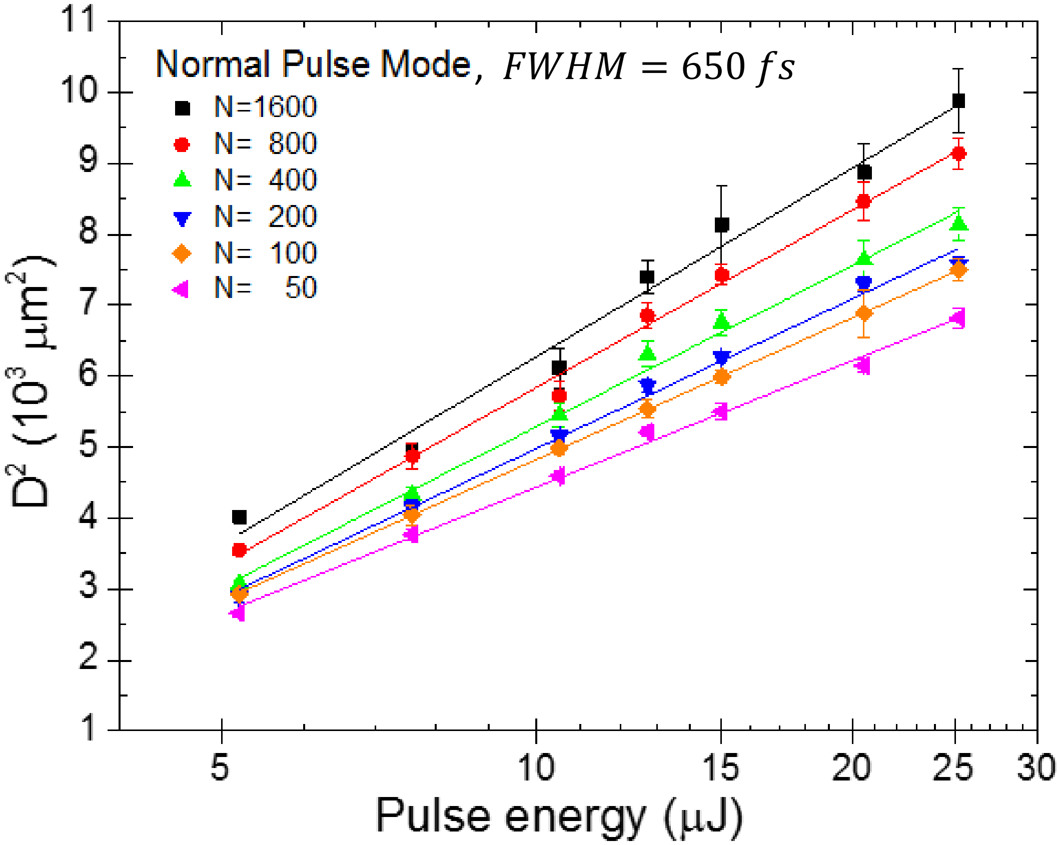
$$D(N)^2 = 2w^2(ln\Phi_0 - ln\Phi_{th}(N))$$

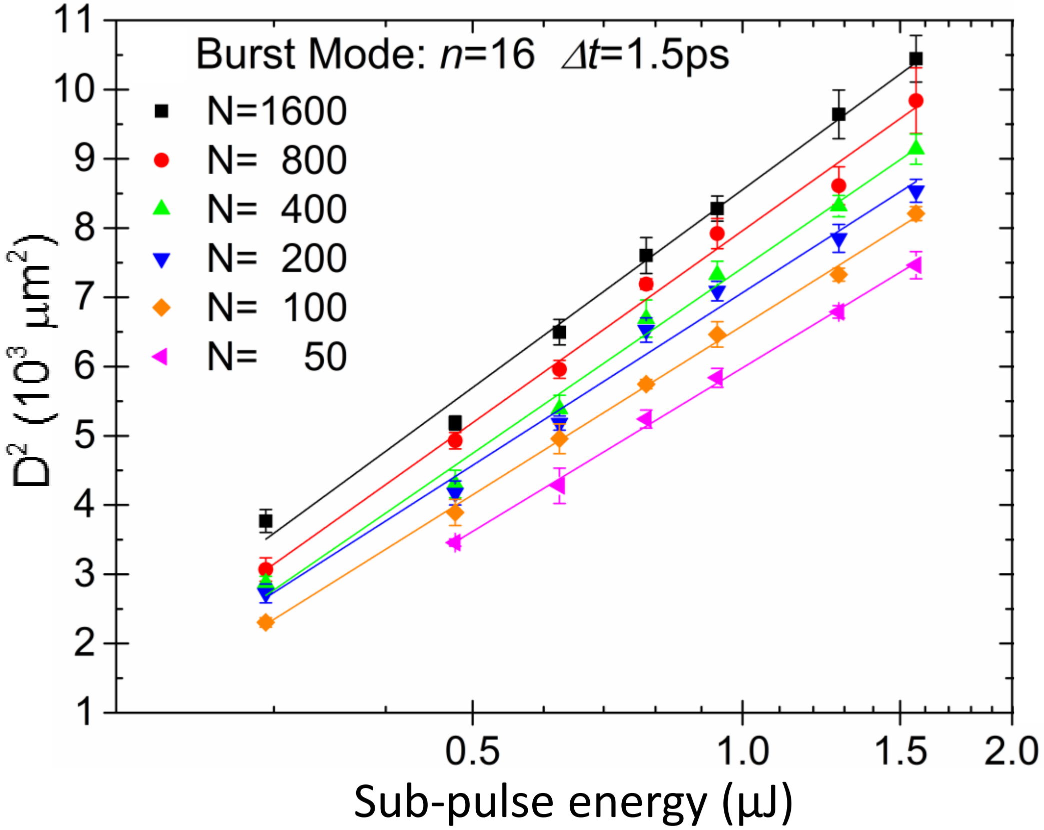
D	crater diameter
N	number of pristine pulses
w	laser spot radius
Φ_0	peak fluence
Φ_{th}	ablation threshold fluence
E	pulse energy

$$\left(\Phi = \frac{2E}{\pi w^2}\right)$$

Burst features

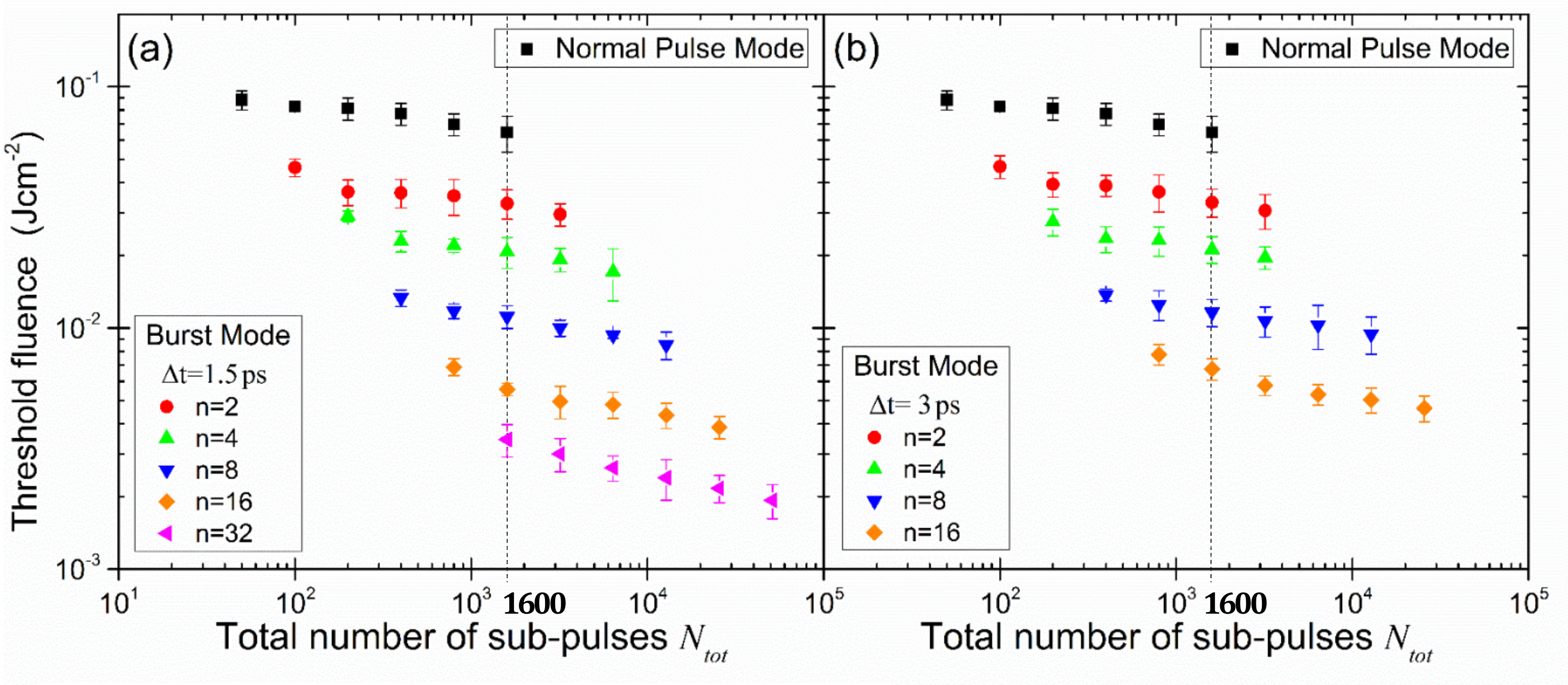
Number of sub-pulses, n	2, 4, 8, 16, 32
Intra-burst time delay, Δt	1.5 ps, 3 ps
Burst polarization, P	CP





PhD student: Giuseppe Giannuzzi

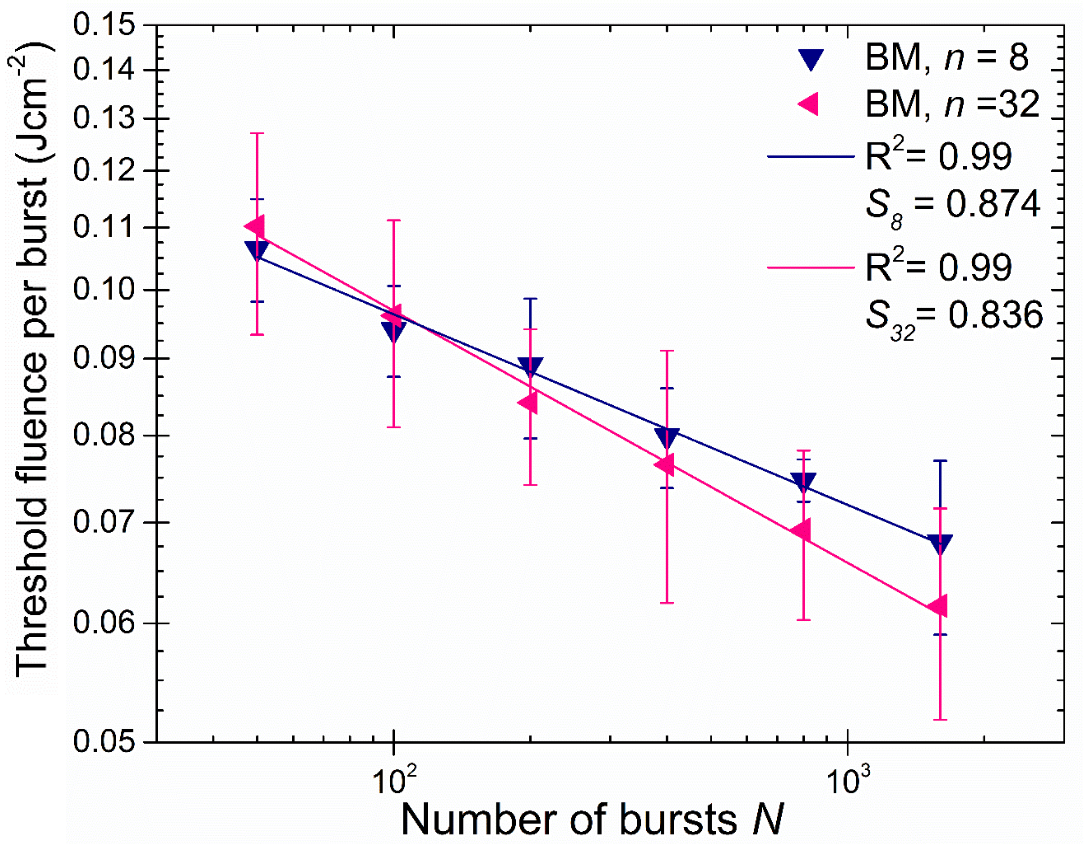
Ablation threshold fluence Φ_{th} decreases with N_{tot}



Number of bursts N	Sub-pulses in the burst n	Total number of sub-pulses $N_{tot} = N \cdot n$	Threshold fluence F_{th} (J/cm^2) $\Delta t = 1.5\ ps$	$\Delta t = 3\ ps$
800	2	**1600**	0.0328	0.0332
400	4		0.0207	0.0211
200	8		0.0111	0.0116
100	16		0.0056	0.0067
50	32		0.0034	

PhD student: Giuseppe Giannuzzi

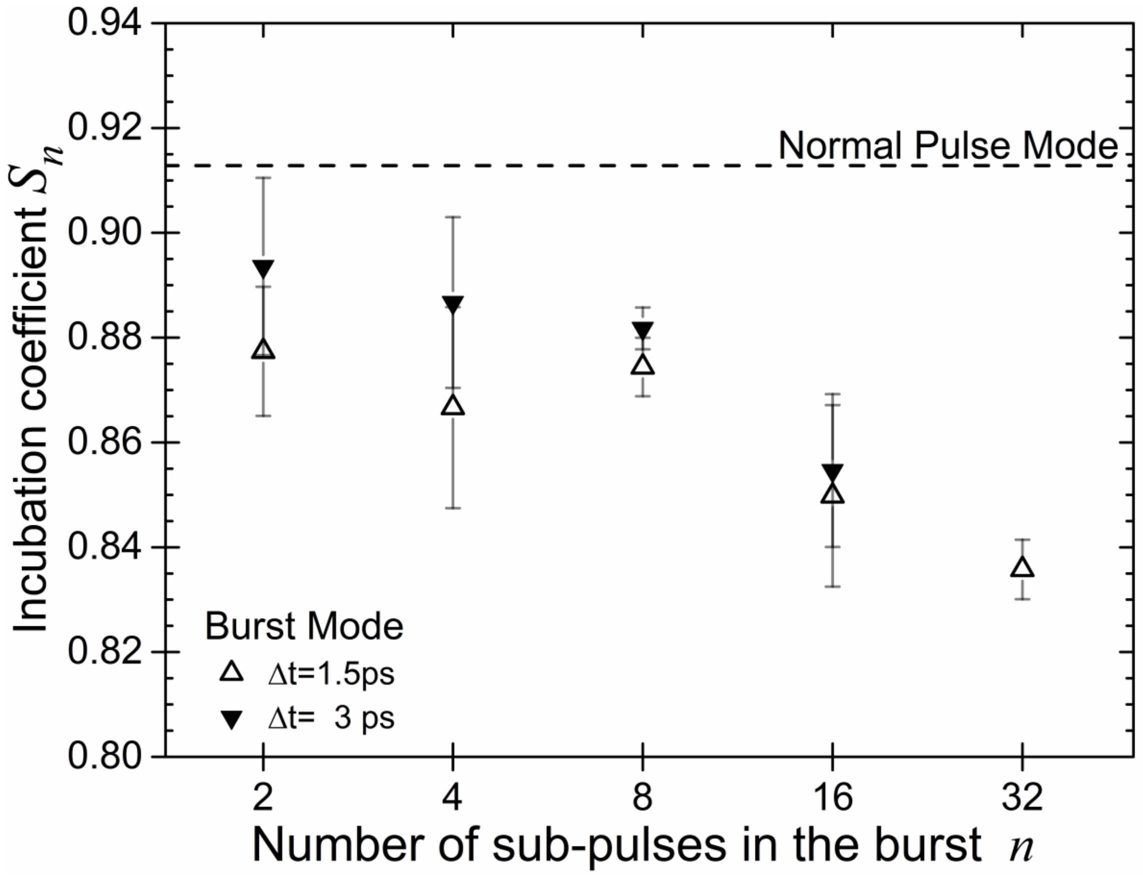
Threshold fluence per burst $\Phi_{th,b}$ and incubation model



$$\Phi_{th,b}(N) = \Phi_{th,b}(1)\ N^{S_n - 1}$$

$\Phi_{th,b}(1)$	threshold fluence for N bursts
$\Phi_{th,b}(N)$	threshold fluence for a single burst
S_n	incubation coefficient

Incubation in Burst Mode



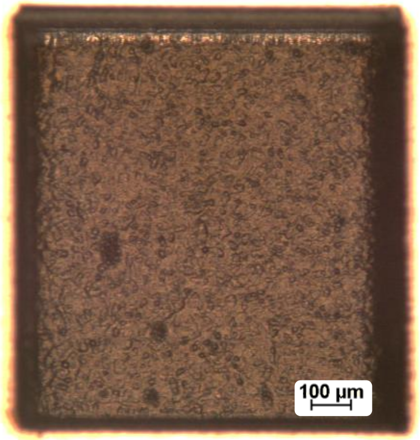
Incubation effect with bursts of fs-sub-pulses is stronger with respect to NPM

Incubation depends on the burst features

The reduction of the threshold fluence observed in BM,
led to increase the removal rate?

C. Gaudiuso, G. Giannuzzi et al., Opt. Express, vol. 26, p. 3801 (2018).

Ablation removal rate during laser milling in NPM and BM

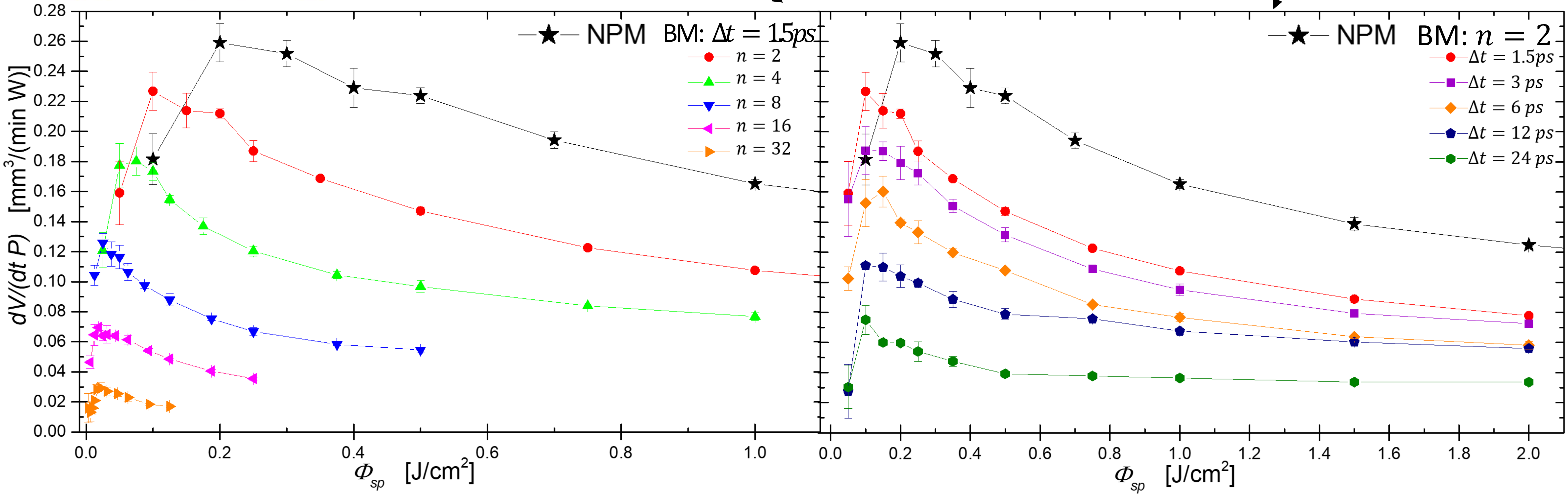


$$\frac{\dot V}{P_{av}} = \frac{\Delta V_{sp}}{E_{sp}}$$

$\dot V / P_{av}$ specific removal rate
ΔV_{sp} sub-pulse ablated volume
E_{sp} sub-pulse energy
Φ_{sp} sub-pulse fluence

Burst features in experiments

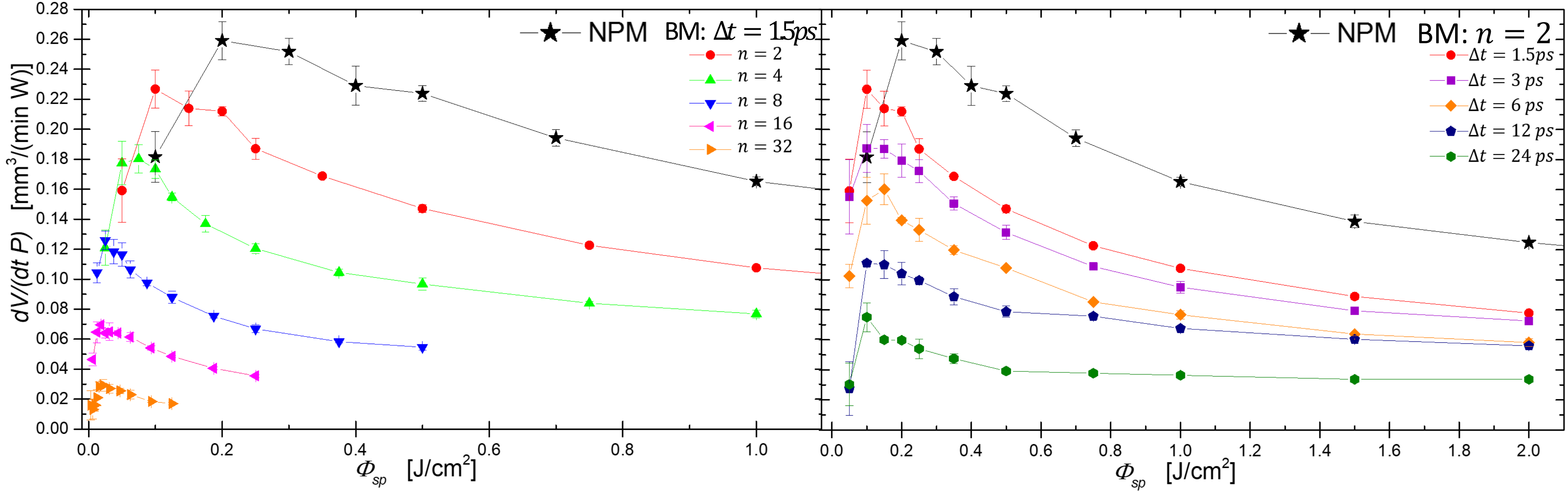
$\Delta t = 1.5\ ps$	$n = 2$
$n = 2 \div 32$	$\Delta t = 1.5 \div 24\ ps$



PhD student: Giuseppe Giannuzzi

Ablation removal rate during laser milling in NPM and BM

- The BM specific removal rate was always lower that the maximum specific removal rate obtained in NPM
- The laser-matter interaction of first sub-pulses in the burst probably induced shielding or scattering of subsequent ones
- Some burst configurations led a higher removal rate than NPM in a narrow window of process conditions at low fluence



PhD student: Giuseppe Giannuzzi

Laser-induced periodic surface structures – LIPSS

LSFL

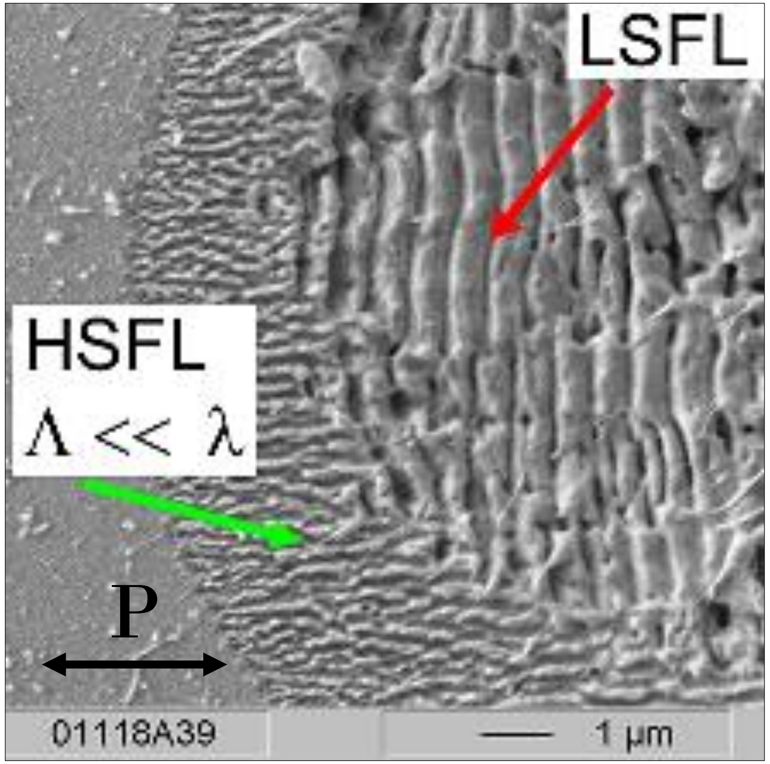
Low Spatial Frequency LIPSS

$$\lambda/2 \leq \Lambda_{LSFL} \leq \lambda$$

HSFL

High Spatial Frequency LIPSS

$$\Lambda_{HSFL} < \lambda/2$$

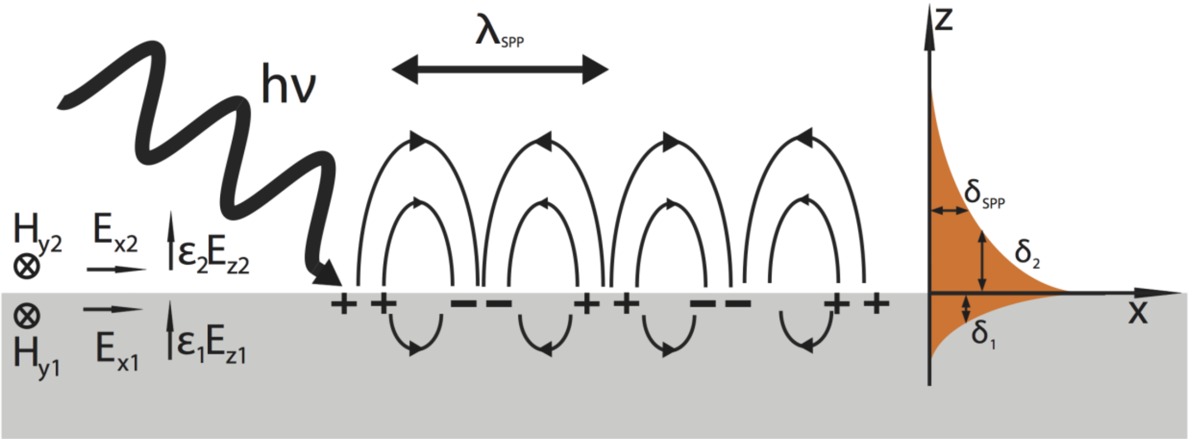


C.K.Schmising, Material modification with femtosecond laser pulses

Interference of the incident light with Surface Electromagnetic Wave (SEW) excited by irradiation: periodic pattern of laser energy absorption on the irradiated surface

The spatial period of the modulated electromagnetic field of the Surface Plasmon Polariton (SPP) can be estimated

$$\lambda_{SPP} = \lambda \left(\frac{\varepsilon' + \varepsilon_d}{\varepsilon' \varepsilon_d} \right)^{1/2}$$



M. Huang, ACS Nano **3**, 4062 (2009)   J. Zhang, J. Phys. D: Appl. Phys. **45**, 113001 (2012)

LinearlyPolarized (LP) bursts

$\Phi = 0.85\, J/cm^2$

Overlap: 41.7% horizontal
79.2% vertical

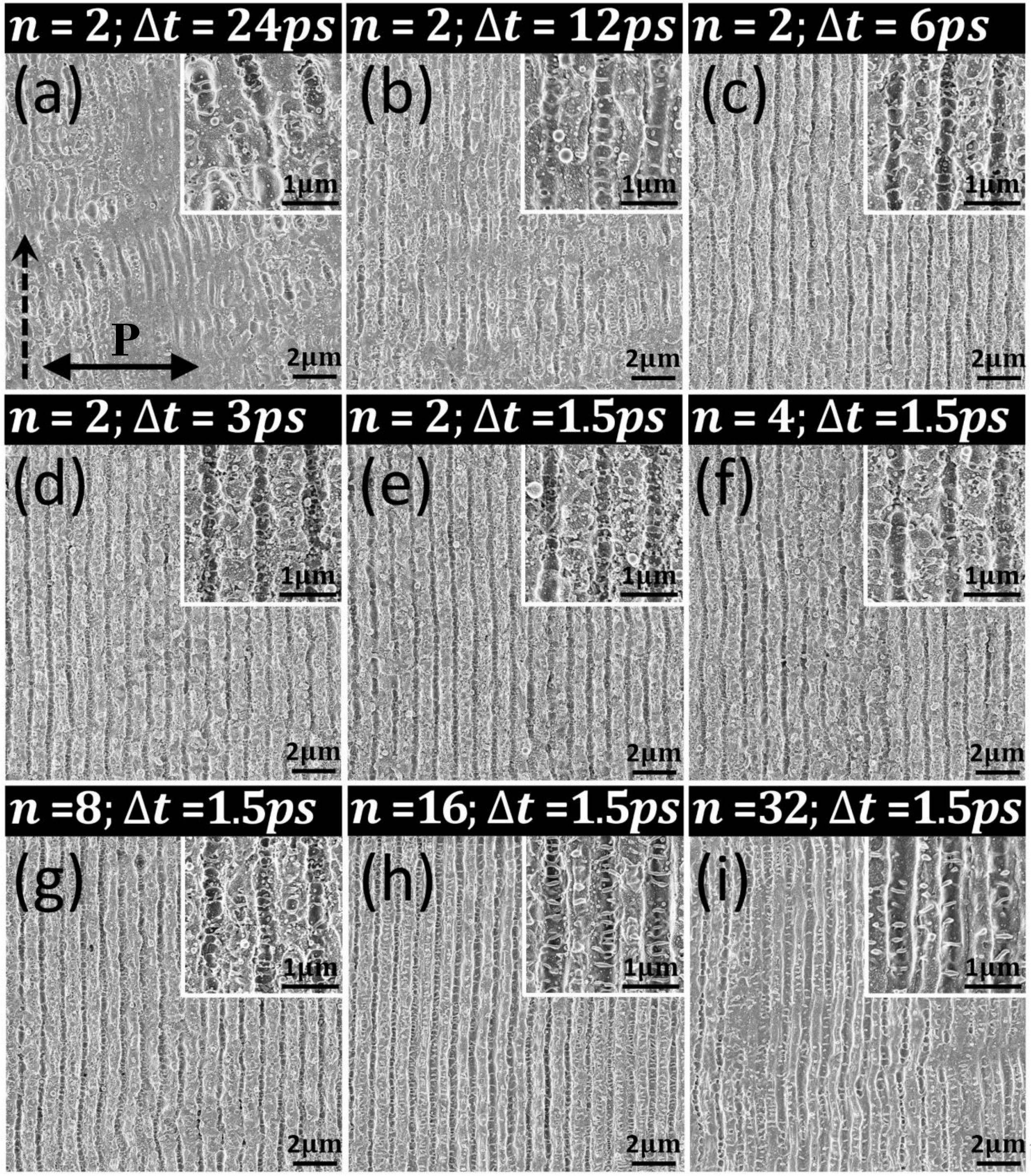
⇓

1D-LSFL

One orientation

Spatial period, Λ

LIPSS morphology changes
with the burst fetaures



Evaluation of LSFL morphology features

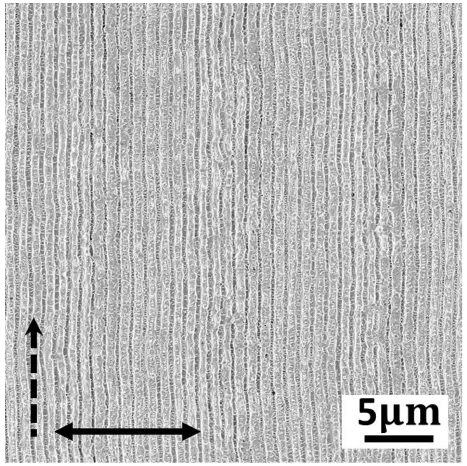
ANALYSIS OF:

- scanning electron microscope (SEM) images → spatial period, Λ
- atomic force microscope (AFM) profiles → depth, Δz

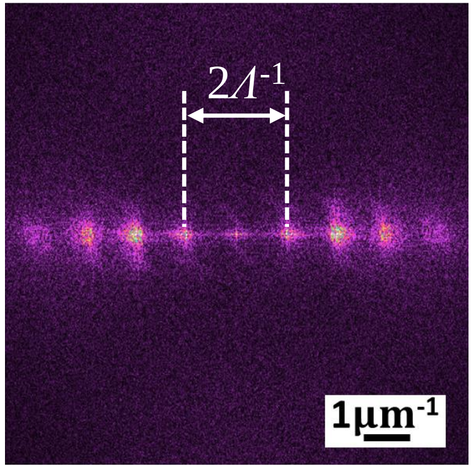
EVALUATION OF:

spatial period, Λ

depth, Δz

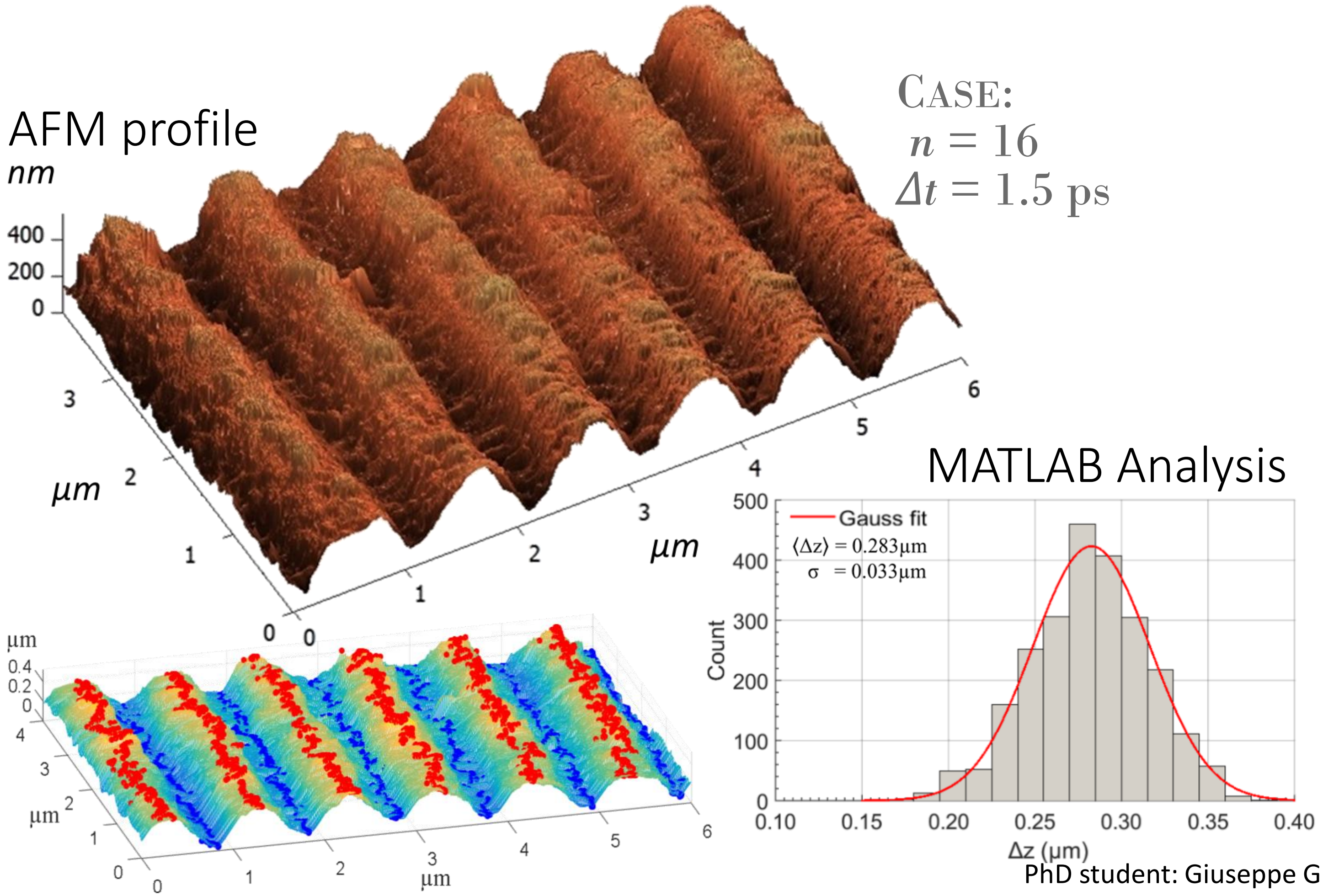


SEM image



2D-FFT

AFM profile



CASE:

$n = 16$

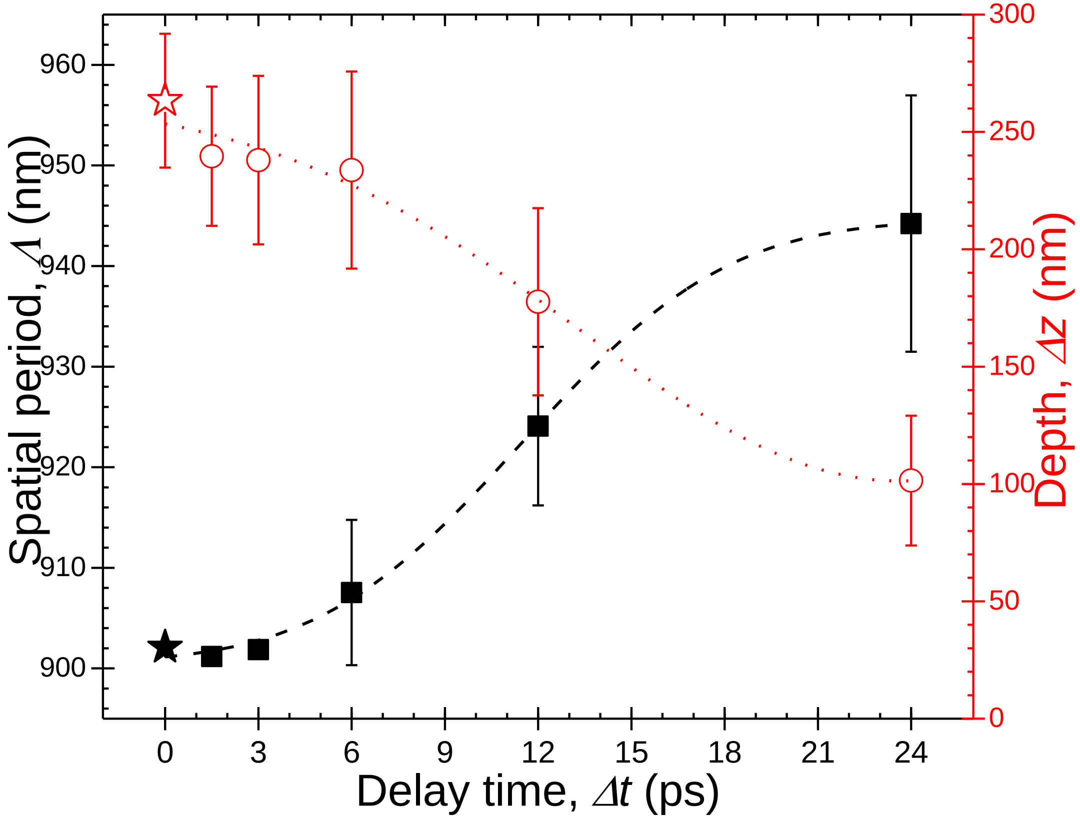
$\Delta t = 1.5$ ps

MATLAB Analysis

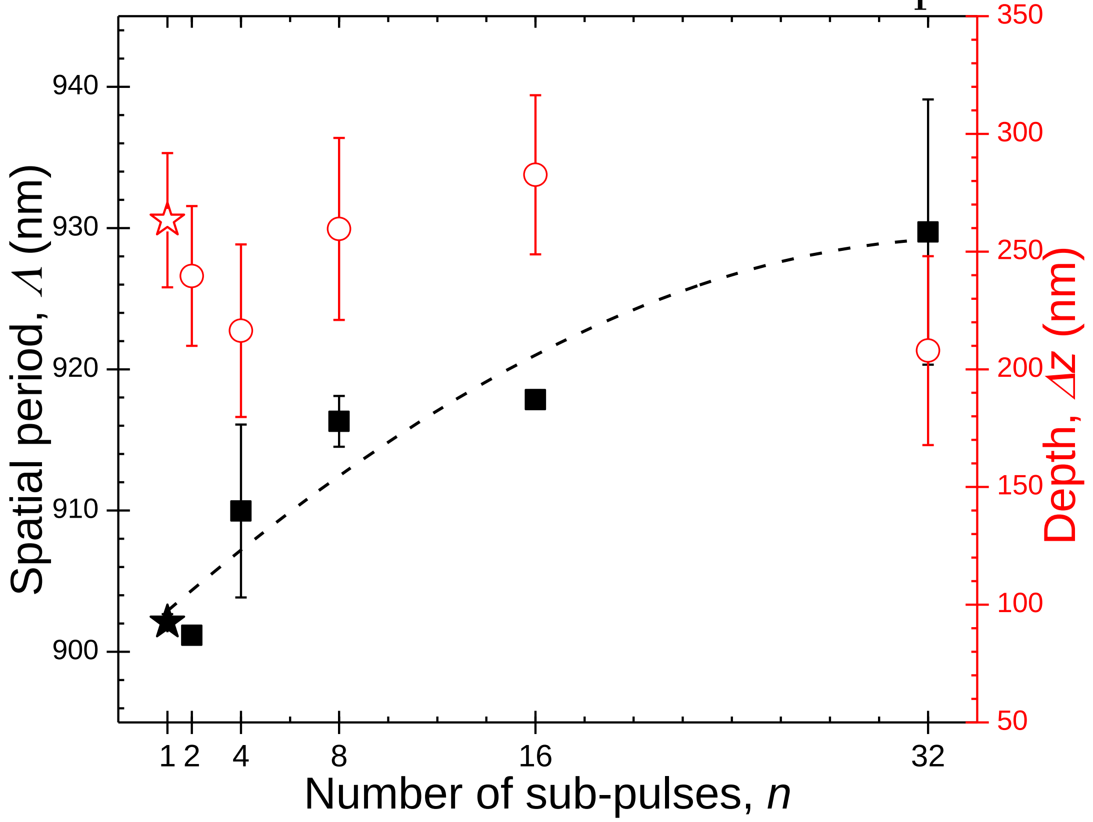
PhD student: Giuseppe Giannuzzi

Influence of the burst features on LSFL morphology

BURST OF $n = 2$ SUB-PULSES



INTRA-BURST TIME DELAY OF $\Delta t = 1.5$ ps



☆ ★ **Normal Pulse Mode - NPM** ($n = 0$; $\Delta t = 0\ ps$)

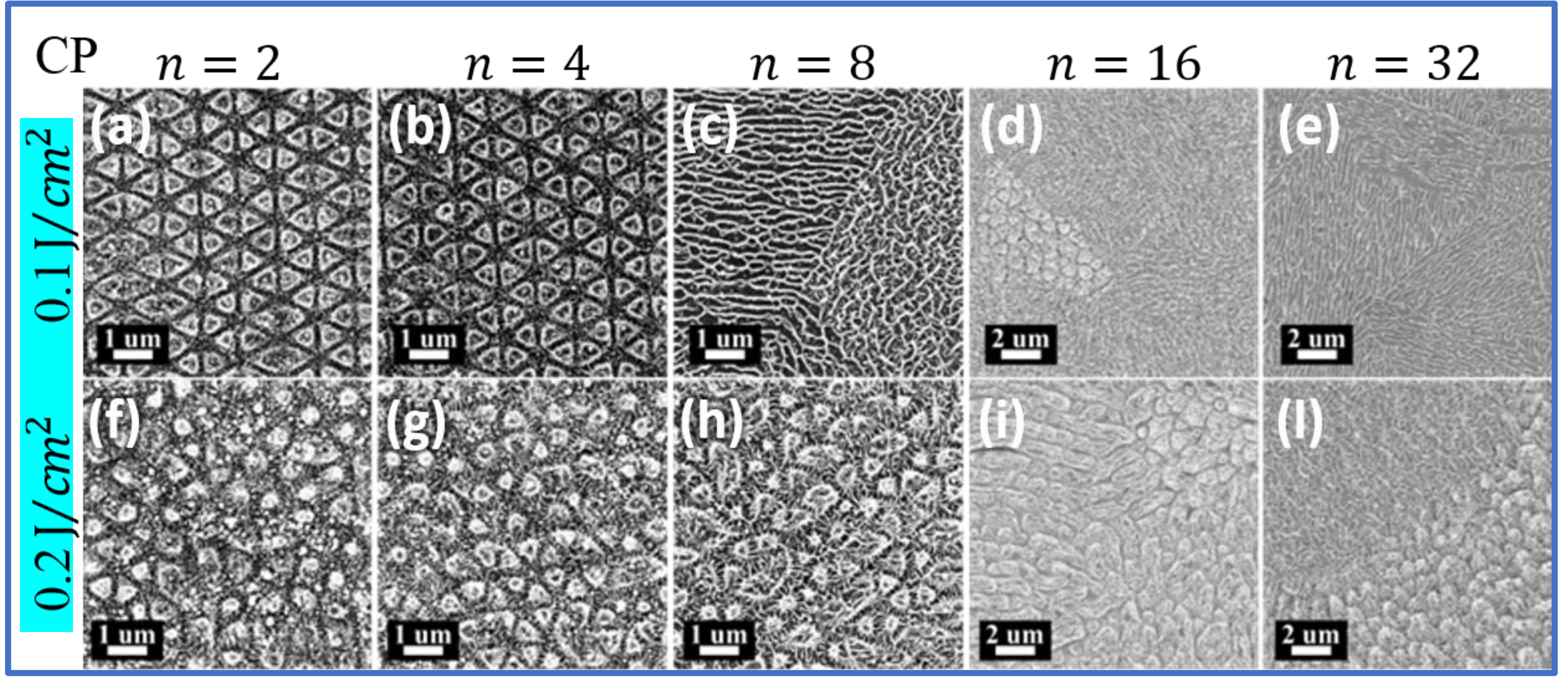
- Spatial period increases with *n* and Δt
- The depth decreases with the intra-burst delay due to a shielding effect
- Dependence of the LSFL depth on *n* ascribed to:
  - shielding effect [A. Semerok et al., Thin Solid Films 453 (2004)]
  - incubation effect [C. Gaudiuso, G. Giannuzzi et al., Opt. Express., 4 (2018)]

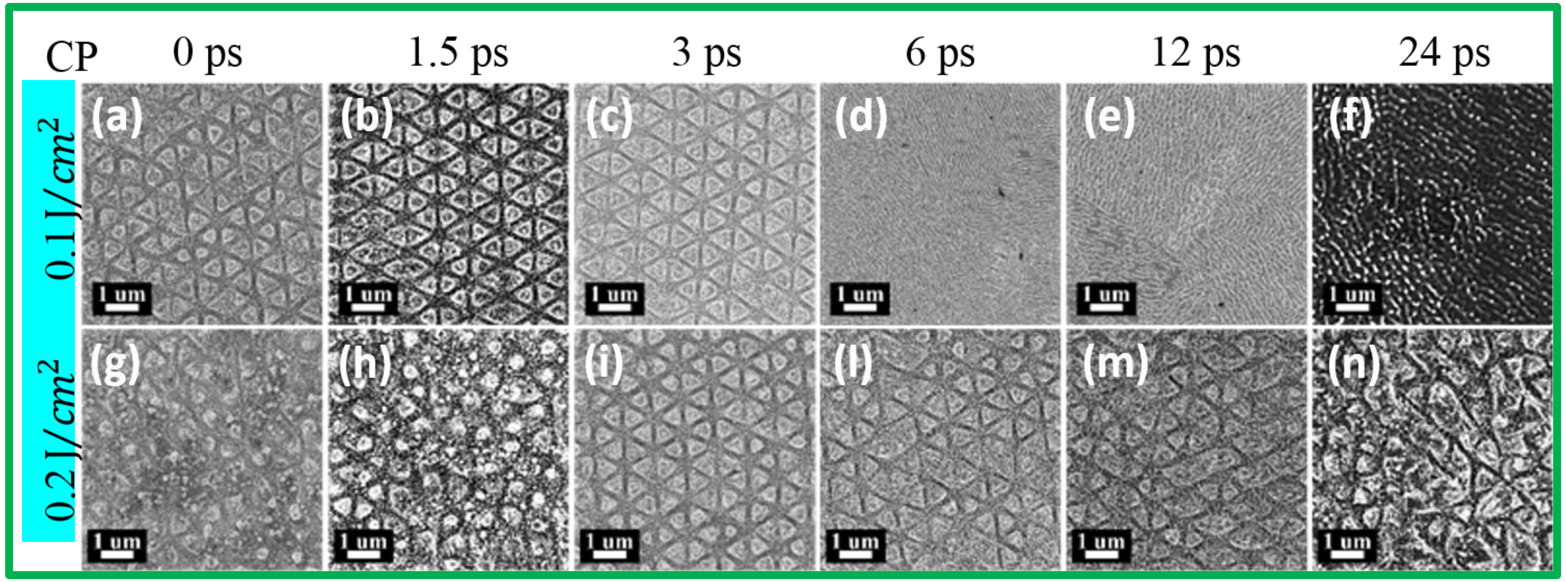
G. Giannuzzi et al., Opt Lasers Eng, vol. 114, p. 15–21 (2019).

CIRCULARLY POLARIZED (CP) BURSTS

Varying: number of sub-pulses
intra-burst time delay
fluence

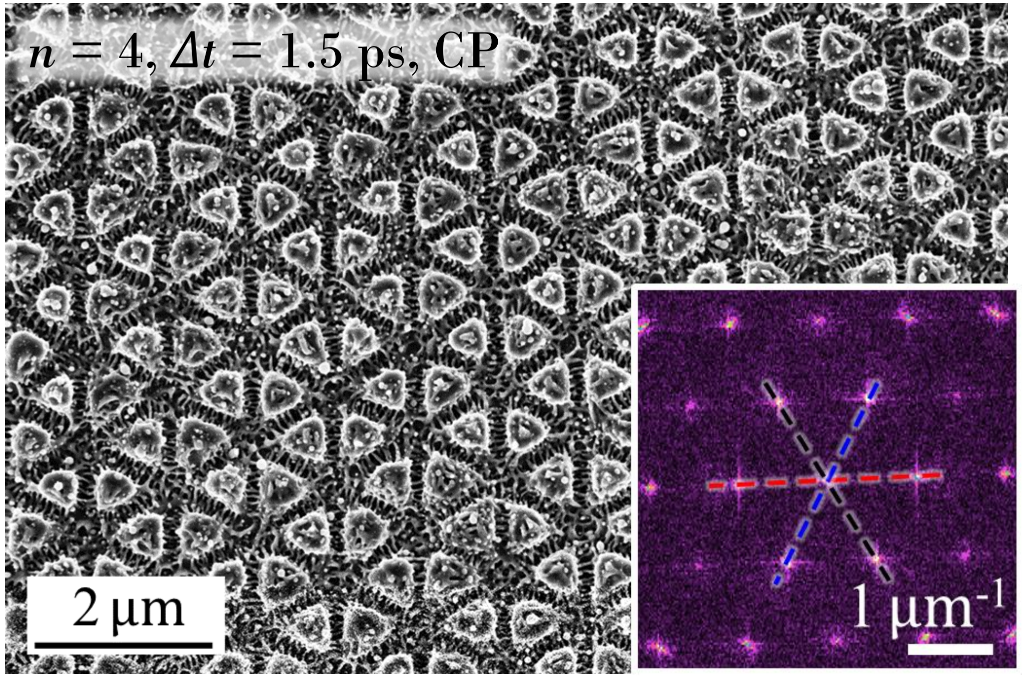
- triangular 2D-LIPSS are obtained in narrow parameter windows
- increasing the pulse splitting (*n*) and the time delay, the HSFL are oriented along the crystal grains
- increasing the fluence, the ordered structures are erased in favour of pillars
- analogue results in XP bursts





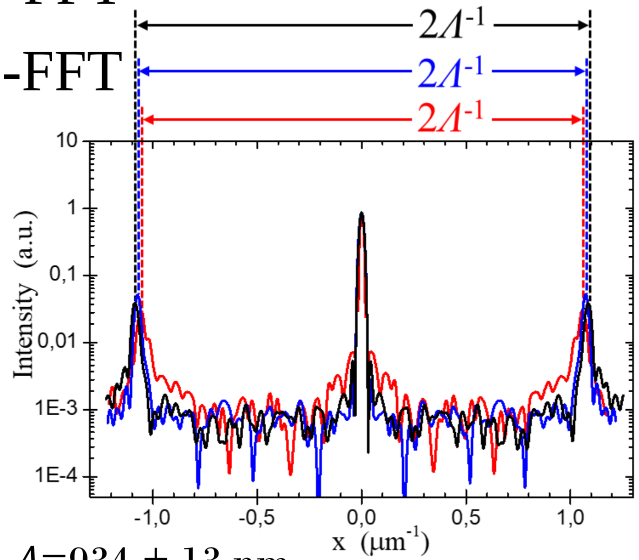
PhD Student: GIANNUZZI Giuseppe giuseppe.giannuzzi@uniba.it

Evaluation of 2D-LSFL morphology features



SEM image+2D-FFT

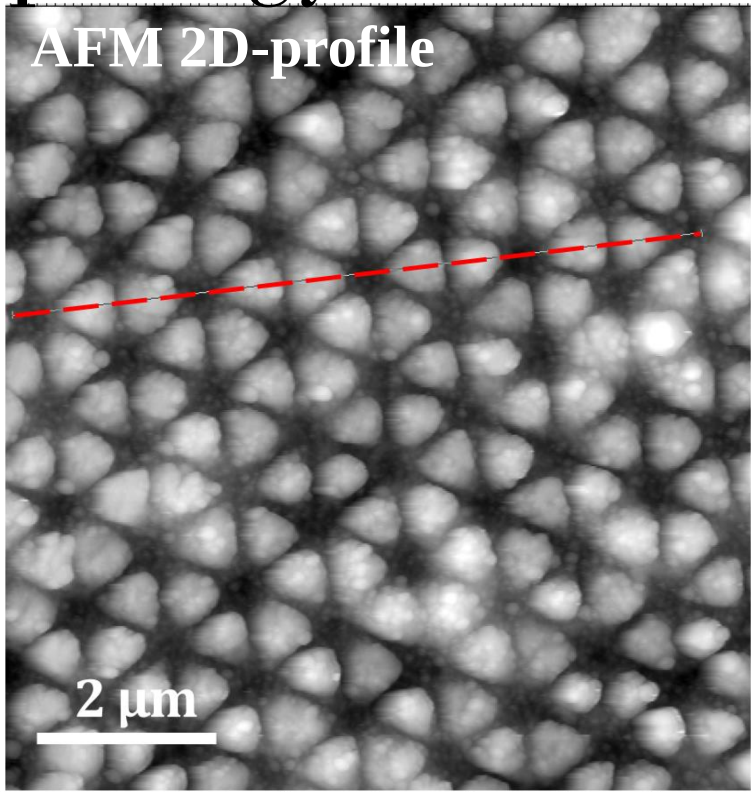
1D-FFT



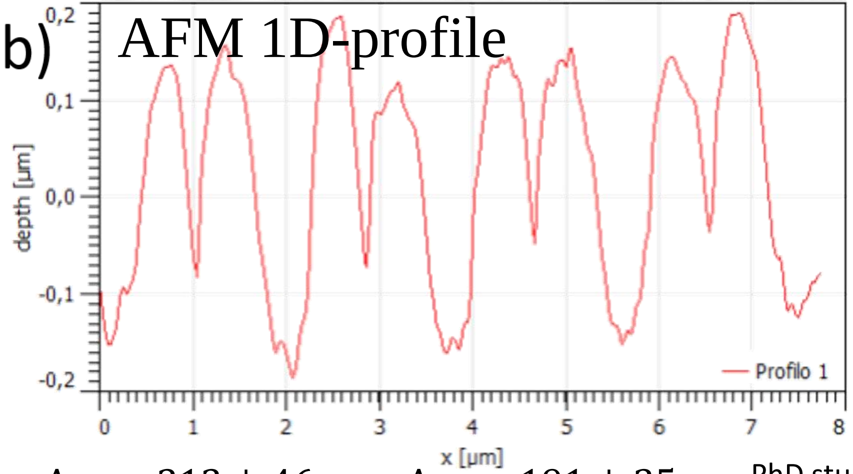
- hexagonal arrangement
- 3 periodic orientations

Λ=934 ± 13 nm

(a)

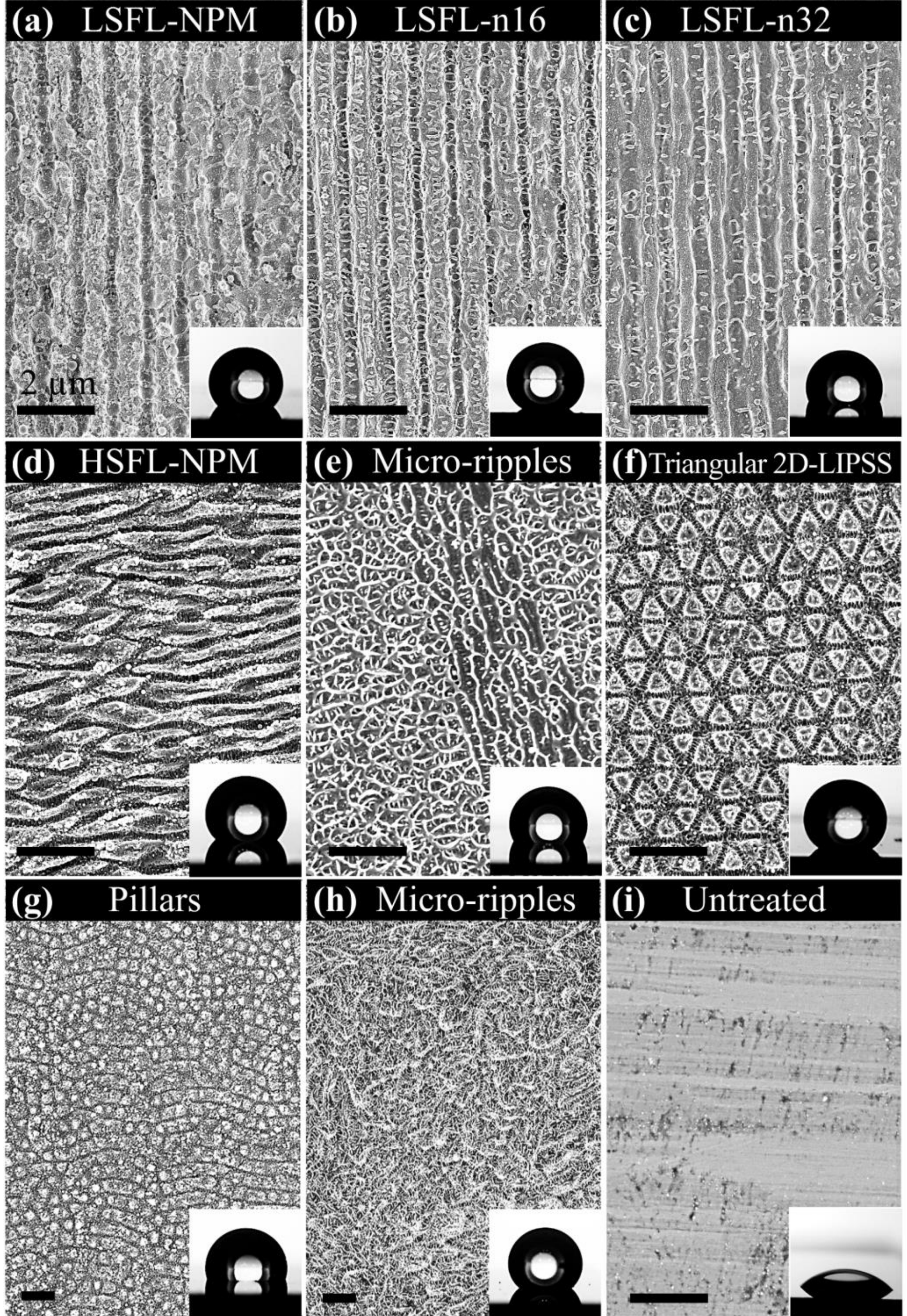


(b)


AFM 1D-profile

$\Delta z_1 = 313 \pm 46\,nm;\ \Delta z_2 = 191 \pm 35\,nm$

PhD student: Giuseppe Giannuzzi

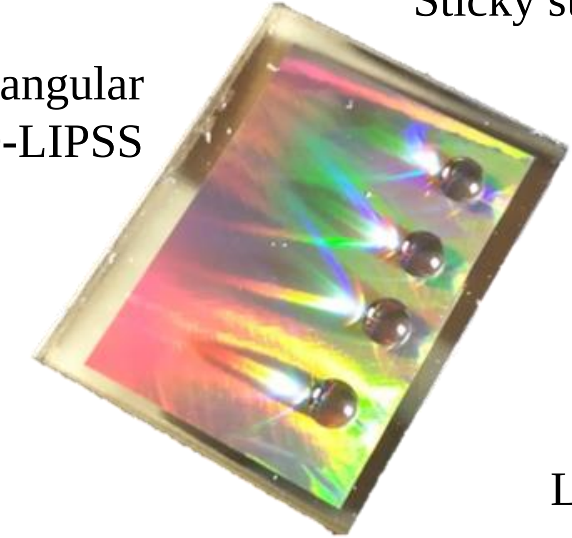


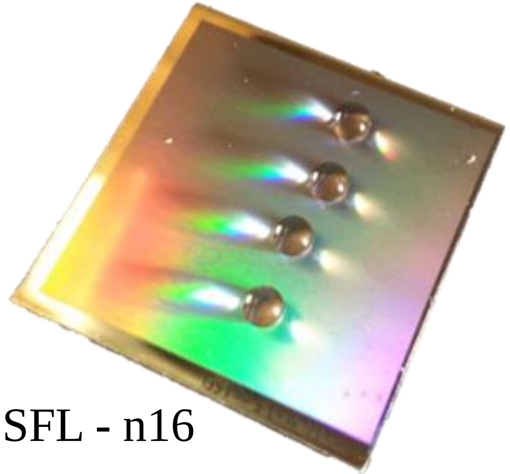
WETTABILITY

	Static	Dynamic
Sample	WCA	H
LSFL - NPM	150.2° ± 1.6°	144° ± 3°
LSFL - n16	160.1° ± 1.5°	138° ± 9°
LSFL - n32	138.7° ± 1.3°	131° ± 5°
HSFL - NPM	160.6° ± 1.2°	146° ± 3°
HSFL - BM	145° ± 2°	137° ± 2°
Triangular 2D-LIPSS	155.6° ± 1.3°	128° ± 7°
Pillars	123.7° ± 1.8°	107° ± 4°
Micro-ripples	157.1° ± 1.4°	144° ± 5°
Untreated	55° ± 2°	55° ± 5°

Sticky super-hydrophobic surfaces

Triangular
2D-LIPSS





LSFL - n16

PhD student: Giuseppe Giannuzzi

CONCLUSIONS

- The numerical simulations of the TTM highlight that a more efficient energy transfer is achievable with bursts of ultrashort pulses
- Incubation in BM is stronger than NPM and it increases with the pulse splitting
- In general, the reduction of the threshold fluence with bursts do not imply higher removal rate than NPM, apart in a narrow range of low fluence for some burst configurations.
- Bursts with picosecond delays generate LIPSS which morphology can be varied with the burst features (number of sub-pulses, time delays, polarization)
- The textured surfaces are sticky and super-hydrophobic

Publications

“High versatile LIPSS generation on stainless steel with bursts of ultrashort pulses”, under preparation;

“Double-pulse femtosecond laser setup for sub-wavelength two-dimensional LIPSS on large area stainless steel surfaces”, under preparation;

G. Giannuzzi, C. Gaudiuso, C. Di Franco, G. Scamarcio, P. M. Lugarà and A. Ancona, “Large area laser-induced periodic surface structures on steel by bursts of femtosecond pulses with picosecond delays”, Opt Lasers Eng, vol. 114, p. 15–21 (2019);

C. Gaudiuso, G. Giannuzzi, A. Volpe, P. M. Lugarà, I. Choquet and A. Ancona, “Incubation during laser ablation with bursts of femtosecond pulses with picosecond delays”, Opt. Express, vol. 26, p. 3801 (2018);

Proceeding

G. Giannuzzi, F. Fraggelakis, C. Gaudiuso, C. Di Franco, G. Scamarcio, G. Mincuzzi, R. Kling, A. Ancona “Surface texturing of steel with bursts of femtosecond laser pulses”, LPM2018 (2018)

C. Gaudiuso, G. Giannuzzi, I. Choquet, P. M. Lugarà, A, Ancona, “Incubation effect in burst mode fs-laser ablation of stainless steel samples”, Proc. SPIE 10520 (2018)

Conferences and schools

International School - “Laser Micro/Nanostructuring and Surface Tribology”, Bari, 1-5 October 2018

LPM 2018 – “Laser precision microfabrication”, 19th International Symposium on Laser Precision Microfabrication, Edinburgh, 25-28 June 2018 (contribution: talk).

LiM 2017 - Lasers in Manufacturing, 26-29 giugno, 2017, Monaco di Baviera - Germany (contribution: talk)

IFN-DAY 2017, Istituto di Fotonica e Nanotecnologia,10-11 gennaio, 2017, Bari (contribution: poster)

Award

Outstanding student’s oral presentation award – 19th International Symposium on Laser Precision Microfabrication, LPM2018, 25-28 June 2018, Edinburgh, UK, “Surface texturing of steel with bursts of femtosecond laser pulses”

Thanks for your attention