Quantifying beam filamentation in broad area lasers using information-theory measures

O. Ricardo Mejia Parra, Margarida Facão,
Sergi Torres-Serra, Jordi Tiana-Alsina
Cristina Masoller
Universitat Politecnica de Catalunya
Terrassa, Barcelona, Spain

Optical Pulses in Nonlinear Photonic Devices (OPNPD26)
WIAS Berlin, June 30, 2026

UPC

Càtedra Chip UPC
d'arquitectures avançades
i sistemes fotònics

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE

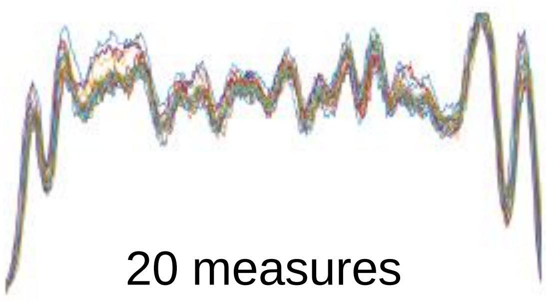
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

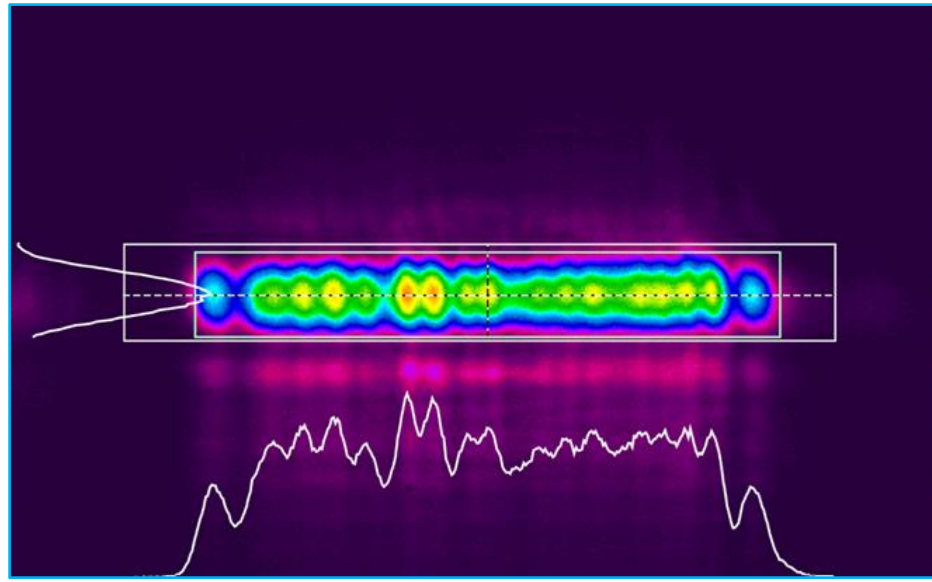
AGAUR
Agència de Gestió d'Ajuts Universitaris i de Recerca

Motivation and research question

- High-power broad-area semiconductor lasers are nowadays widely used in Industrial and Medical applications.

- Problem: Filamentation





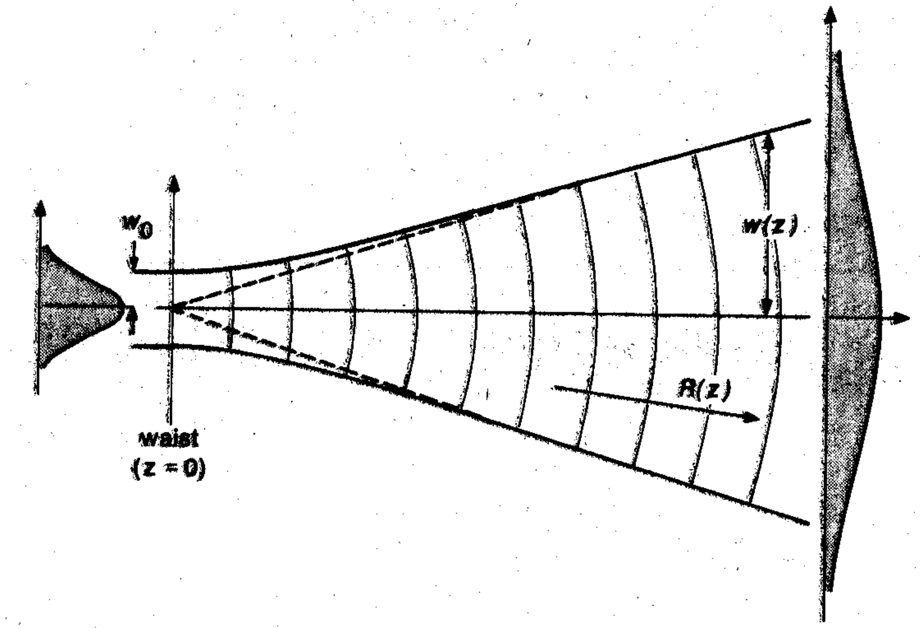
- Question: How to quantify the degree of filamentation?

J. Albiol Serra, *Experimental characterization of filamentation phenomena in pressure-mounted diode laser bars*, Master thesis, Universitat Politècnica de Catalunya (2024) https://hdl.handle.net/2117/423577

monocrom

cristina.masoller@upc.edu @cristinamasoll1

Divergence and beam quality factor (M^2)



The half-angle beam divergence is: $\theta = M^2 \dfrac{\lambda}{\pi w_0}$

- M^2 represents the degree of variation of the propagation of a beam with respect to an ideal Gaussian beam.
- For a single mode TEM_{00} (Gaussian) laser beam, $M^2 = 1$.

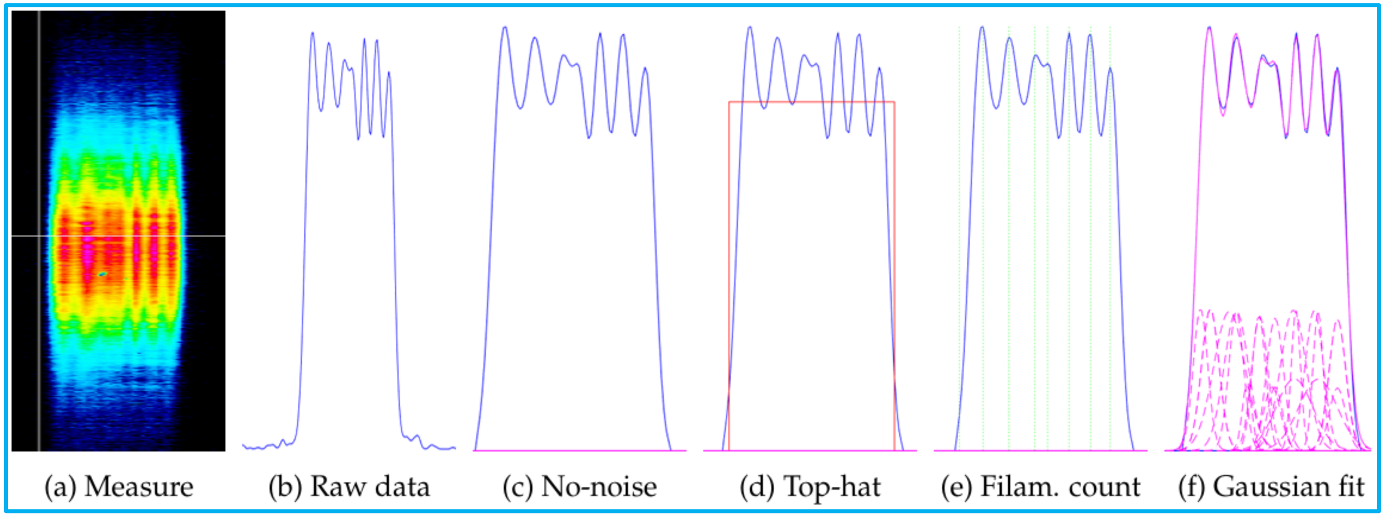
cristina.masoller@upc.edu @cristinamasoll1

Beam parameter product (BPP)

- BPP quantifies how well a laser beam can be focused to a small spot.
- Is the product of a laser beam's divergence angle (θ) and the radius of the beam at its narrowest point (the beam waist, w_0).
- It is related to M^2 as: BPP = $M^2\ \lambda/\pi$
- A Gaussian beam has the lowest BPP, λ/π

cristina.masoller@upc.edu @cristinamasoll1

Previous work on developing metrics for quantifying filamentation



- Sum of squared differences between the top-hat profile and the noise-free profile (drawback: no information of the number of filaments).
- Filament counting (drawback: filament prominence not taken into account).
- Gaussian fit (takes into account the filament widths –drawback: problem to find a fit good enough).

J. Albiol Serra, *Experimental characterization of filamentation phenomena in pressure-mounted diode laser bars*, Master Thesis, Universitat Politècnica de Catalunya (2024)

cristina.masoller@upc.edu @cristinamasoll1

From a one-dimensional profile to a set of probabilities

In theory: a 1D laser beam profile is a function

$$I(x) \geq 0 \text{ with } x \text{ in } [x_i, x_f]$$

In reality (experiments and simulations): the beam profile is a discretized set of numbers, as it is known in a grid of *N* points

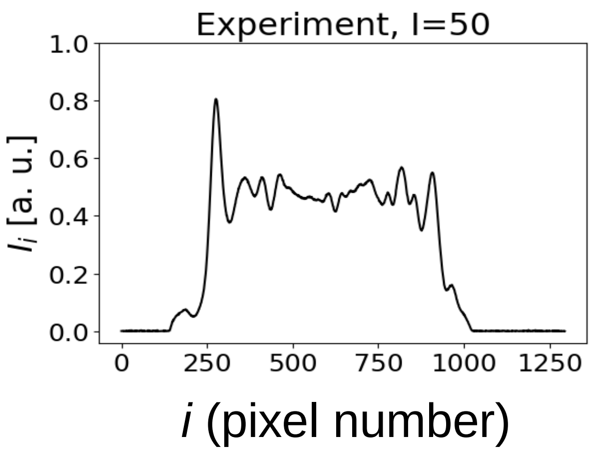
$$I_i \geq 0 \text{ with } i=1\ldots N.$$

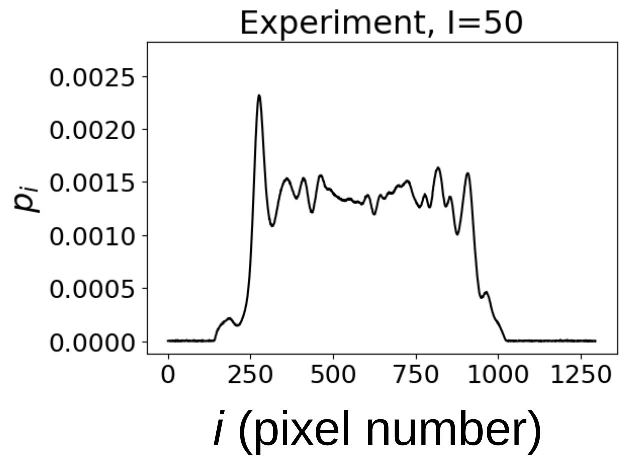
By removing the mean value we transform the beam profile in a set of *N* probabilities $p_i = I_i / (\Sigma I_i)$

$$\boxed{\Sigma p_i = 1}$$

cristina.masoller@upc.edu @cristinamasoll1

Information-theory measures





?

What to do next?

Shannon's entropy:

$$p_i = p_j \; \forall i, j \Rightarrow H=1$$

$$p_i = 1, \; p_j = 0 \; \forall \, j \neq i \Rightarrow H=0$$

$$\boxed{H = -\frac{1}{\ln N!}\sum_{i=1}^{N} p_i \ln p_i}$$

C. Shannon, "A Mathematical Theory of Communication", Bell System Technical Journal. 27 (3): 379–423 (1948). Bell System Technical Journal. 27 (4): 623–656 (1948).

cristina.masoller@upc.edu @cristinamasoll1

A second measure: The Fisher information

(there are different versions of the discrete Fisher information)

$$F = F_0 \sum_{i=1}^{N-1} \left(\sqrt{p_{i+1}} - \sqrt{p_i}\right)^2$$

F_0=1/2 is a normalization constant

F is sensitive to "gradients" in $\{p_1, p_2, \ldots p_N\}$.

$p_i = p_j \ \forall i, j \Rightarrow F=0$

$p_i = 1, p_j = 0 \ \forall j \neq i \Rightarrow F=1$

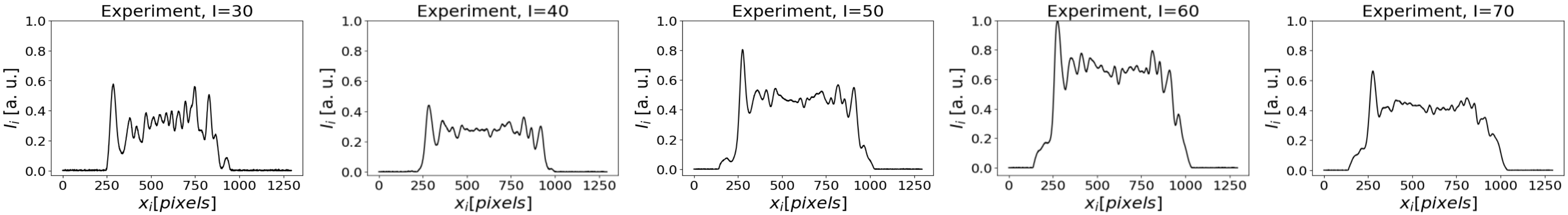
Advantages: *H* & *F* are parameter-free magnitudes that characterize the spatial shape of the laser beam.

Drawback: Information of the mean value is lost.

cristina.masoller@upc.edu @cristinamasoll1

Experimental data analyzed

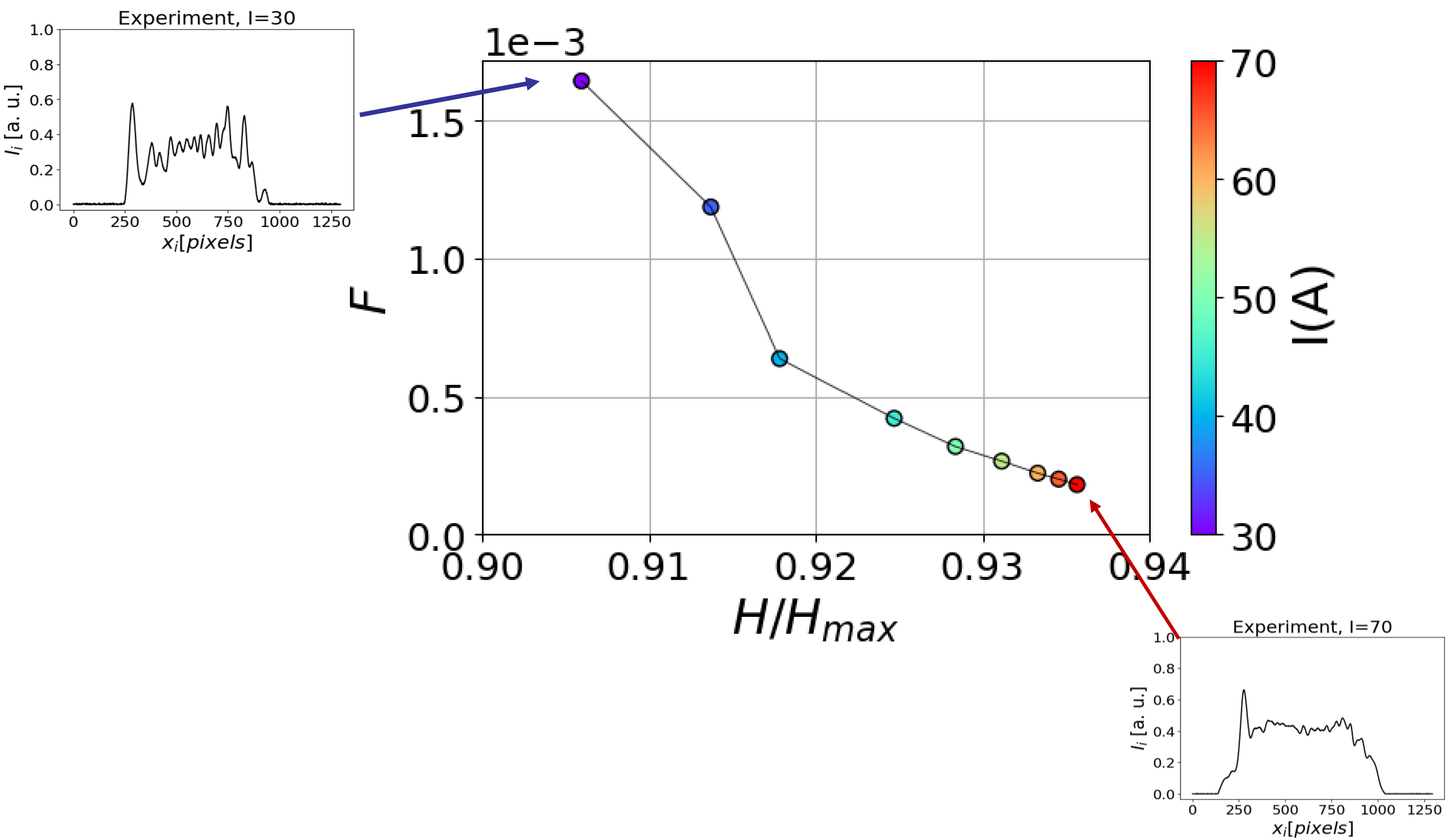
- Near-field profile of a single broad-area semiconductor laser emitter.
- Source: Monocrom laser bar
- Contact width: 200 μm
- Injection currents: 30 A to 70 A
- Number of pixels: 1296



monocrom

cristina.masoller@upc.edu @cristinamasoll1

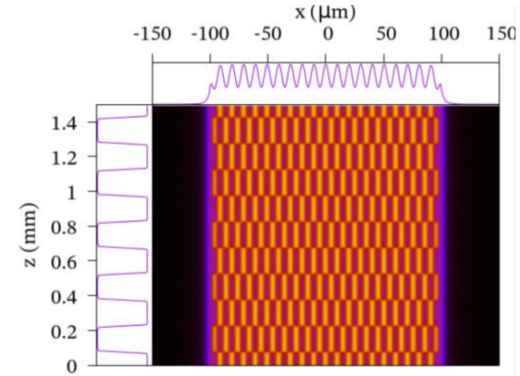
Results



cristina.masoller@upc.edu @cristinamasoll1

Simulated data analyzed

- Source: M. Facão



Pump current spatial pattern

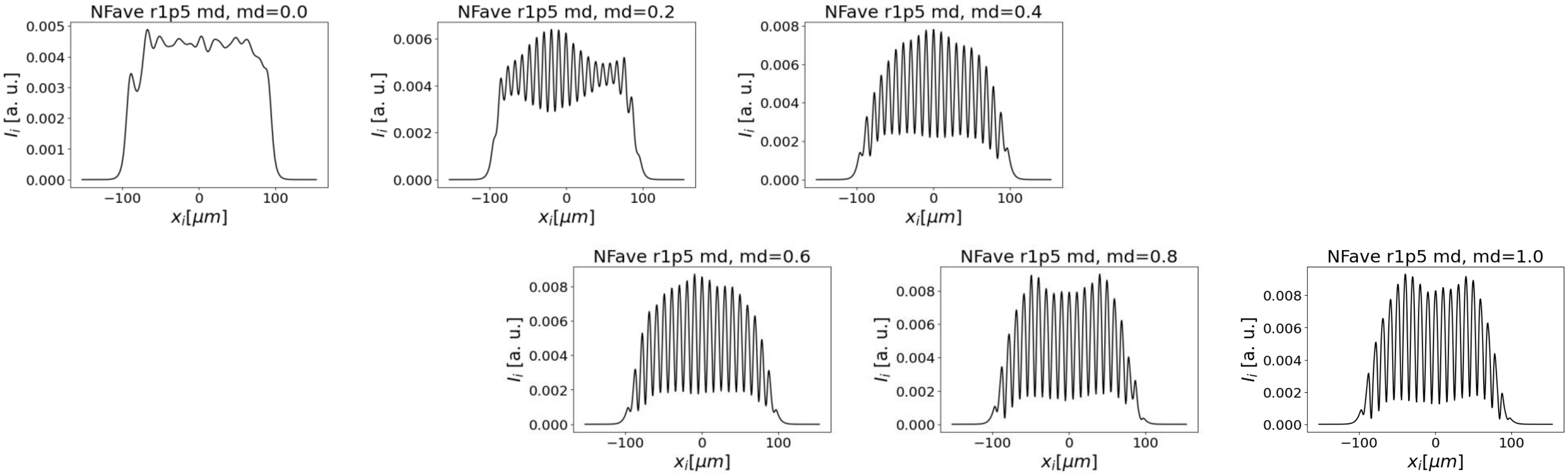
- Near-field (NF) and far-field (FF) profiles
  (averaged over several ns, after transients)

- 11 values of longitudinal modulation strength (md): 0.0 to 1.0
- Two pump currents:
  - I/I_{th} = 1.5
  - I/I_{th} = 6.0
- Number of pixels: 512

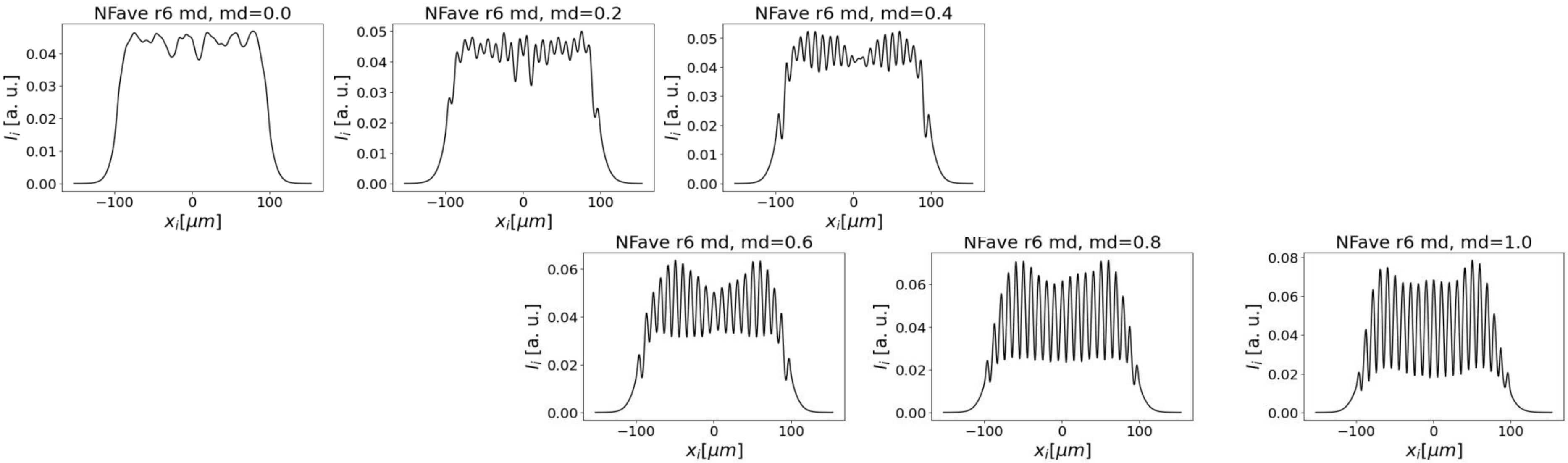
M. Facão et al, "*Effect of transversal and longitudinal current modulation on beam quality in broad area semiconductor lasers*", submitted (2026).

cristina.masoller@upc.edu @cristinamasoll1

Near field profiles for low pump current (I/I_{th} = 1.5):

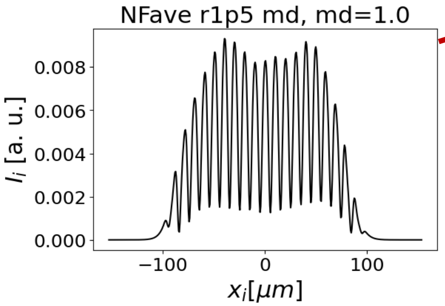


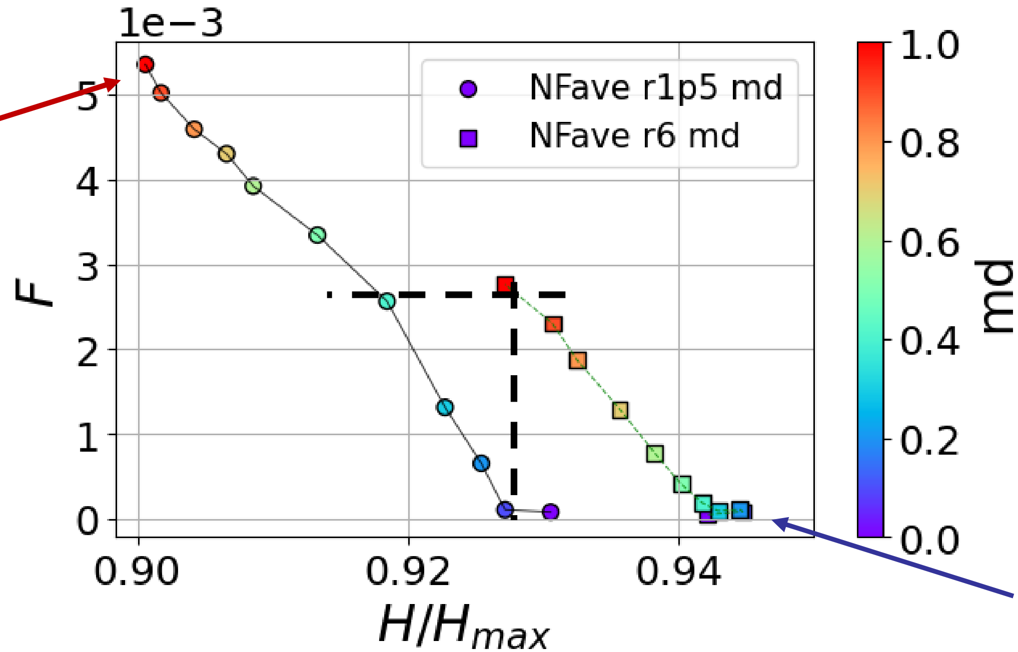
High pump current (I/I_{th} = 6):

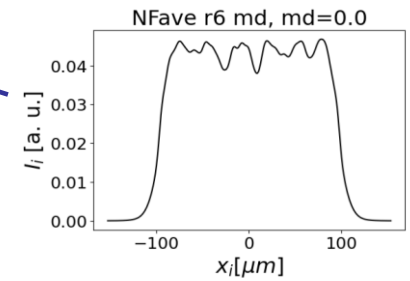


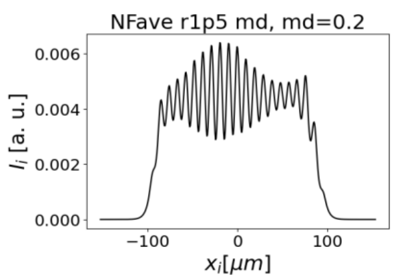
cristina.masoller@upc.edu @cristinamasoll1

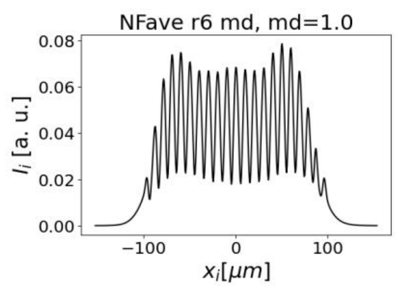
Results



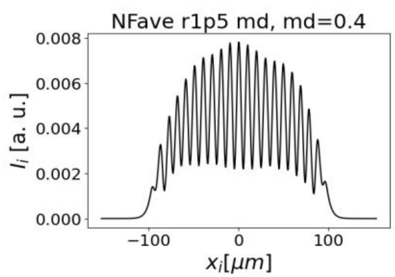


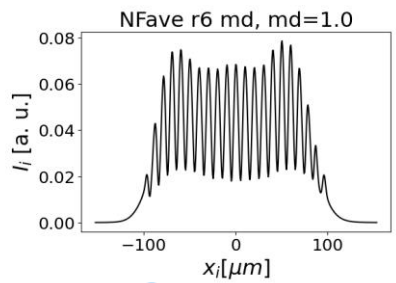






Same H different F

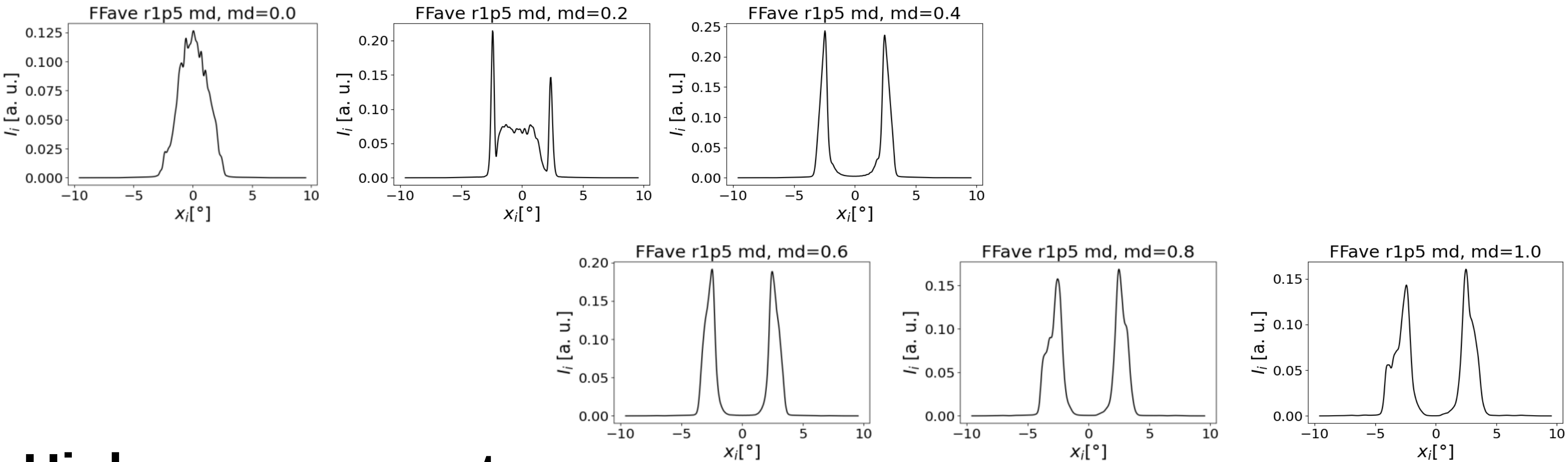




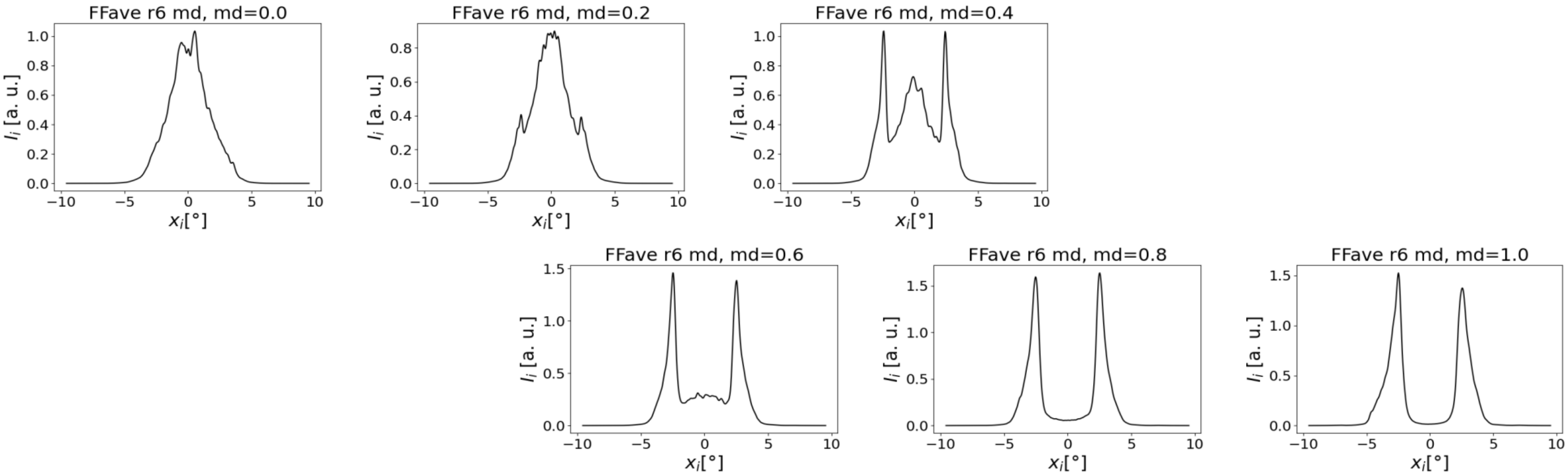
Different H same F

cristina.masoller@upc.edu @cristinamasoll1

Far field profiles for low pump current

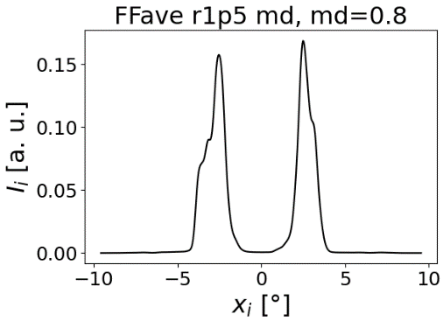


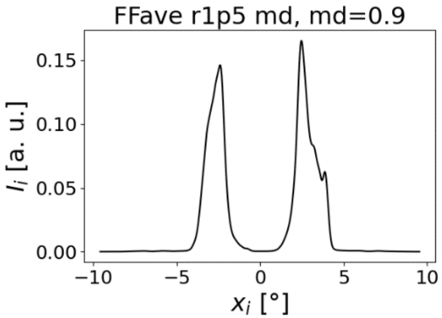
High pump current:

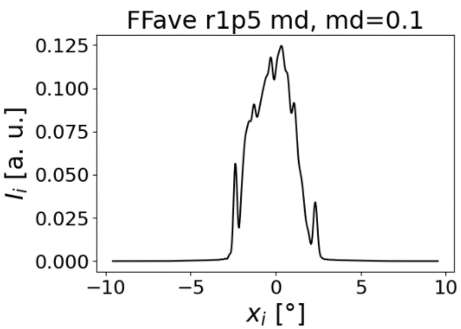


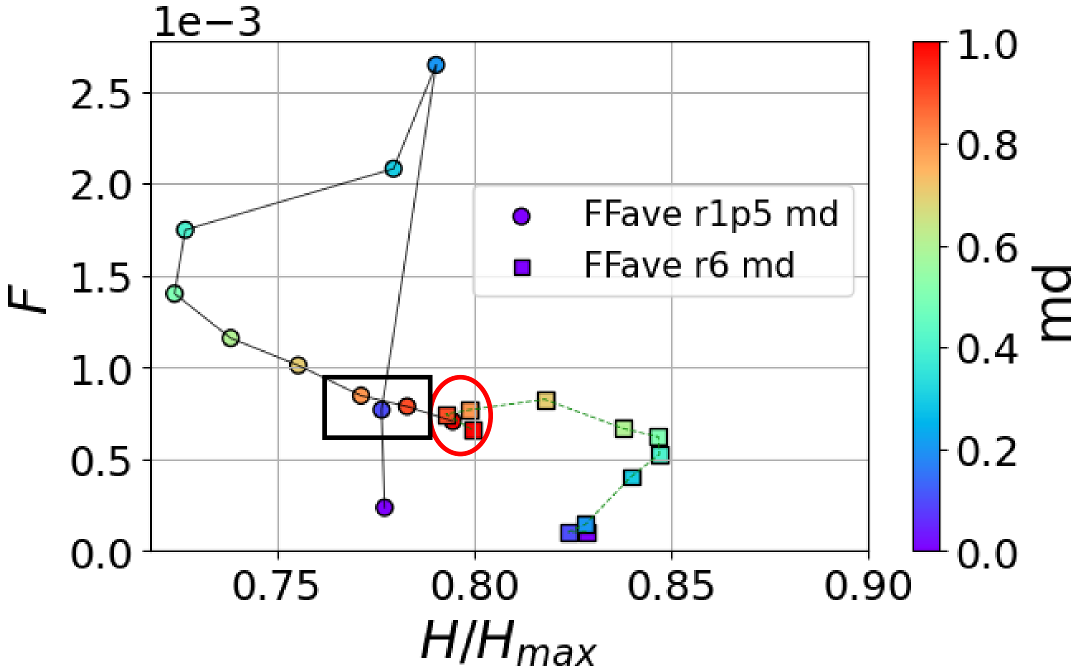
cristina.masoller@upc.edu @cristinamasoll1

Results

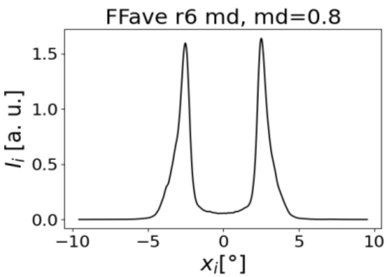


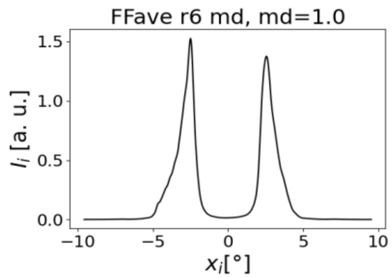


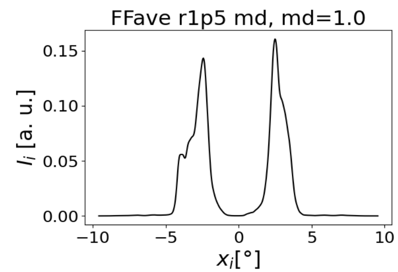




Problem!
F and *H* fail
to quantify
filamentation.

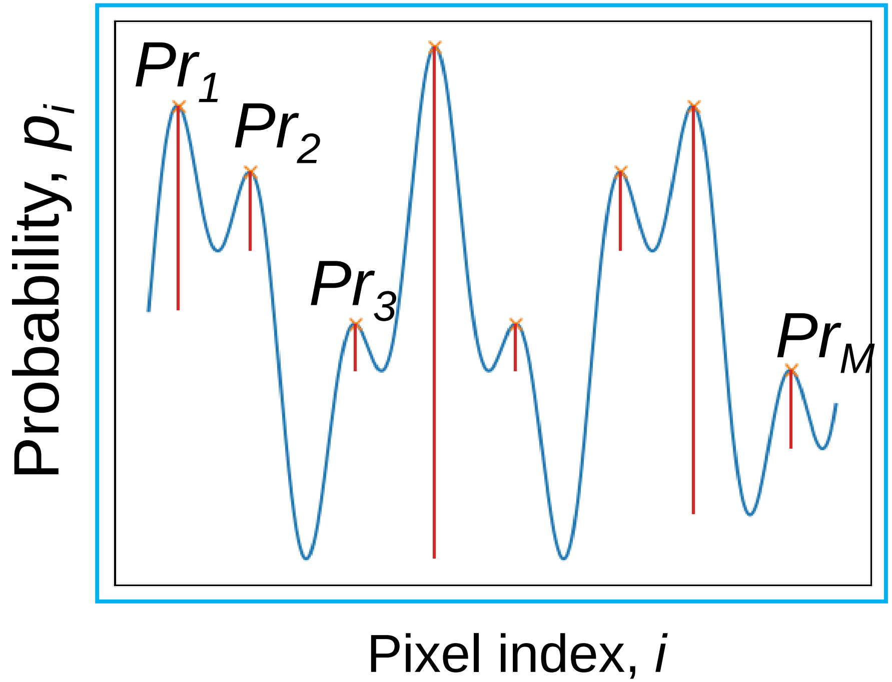






cristina.masoller@upc.edu @cristinamasoll1

Possible solution: peak prominence (ongoing work)



We obtain "features" that can allow to quantify the filamentation:

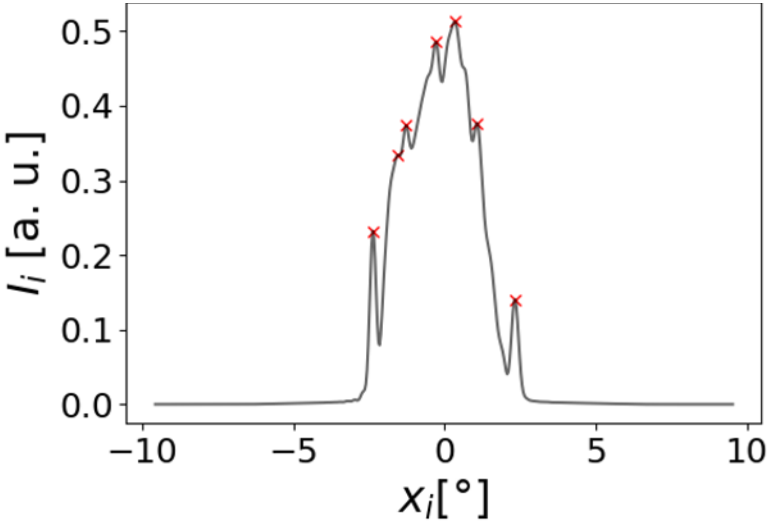
- Np = Number of peaks
- $<Pr>$: Average prominence
- S_{Pr}: Sum of the prominences of the peaks

Python: scipy.signal.find_peaks

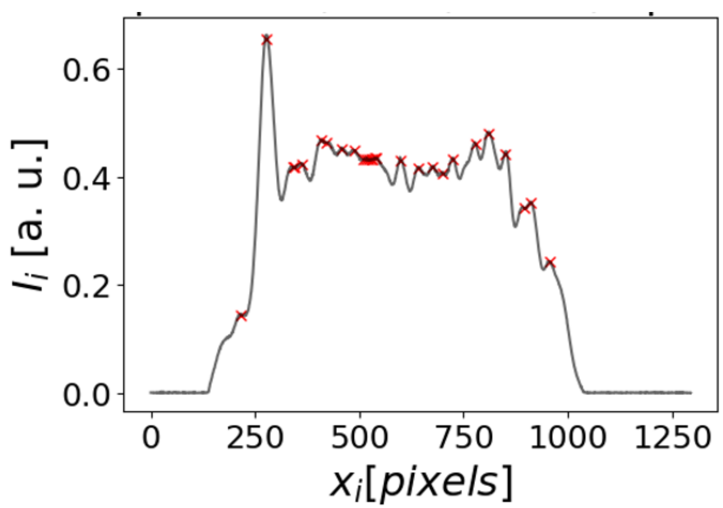
cristina.masoller@upc.edu @cristinamasoll1

Identifying filaments (peaks)

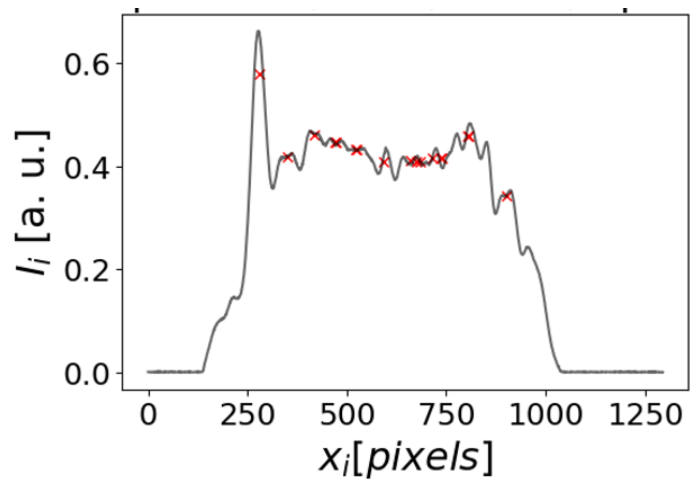
No need to filter if peaks are ``clear'' (w=1: Np=7)



w=10 Np=27



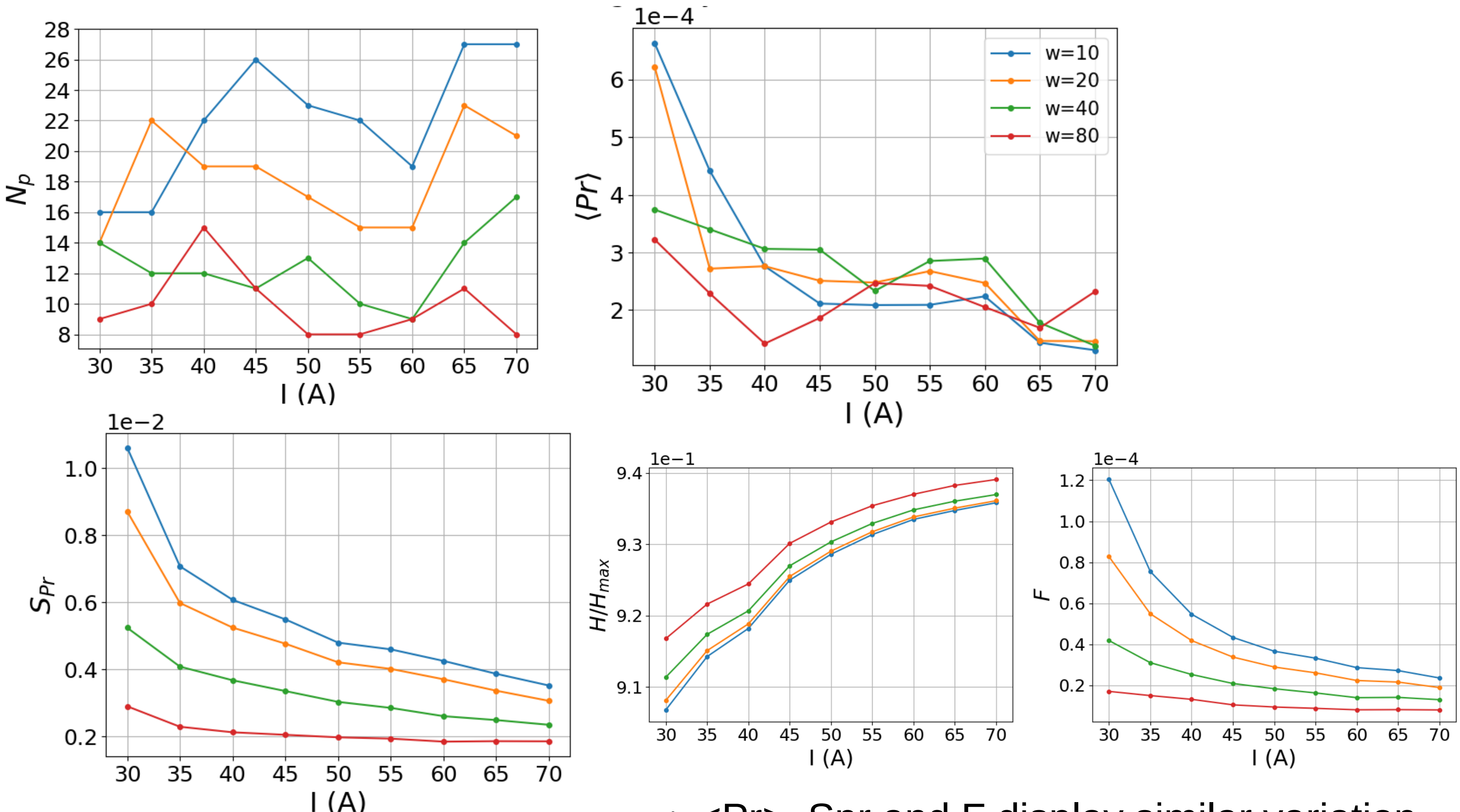
w=40 Np=17



cristina.masoller@upc.edu @cristinamasoll1

Analysis of number of peaks, mean prominence and sum of prominences

Experimental far field profiles

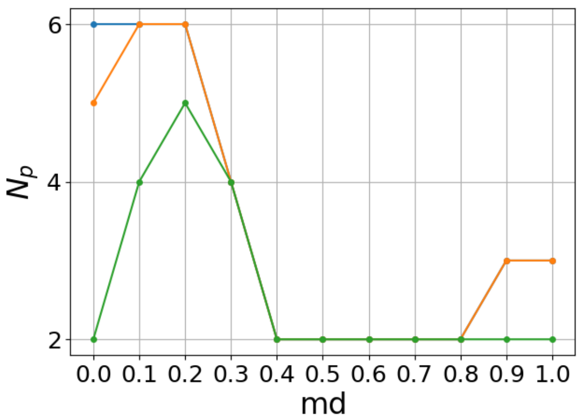


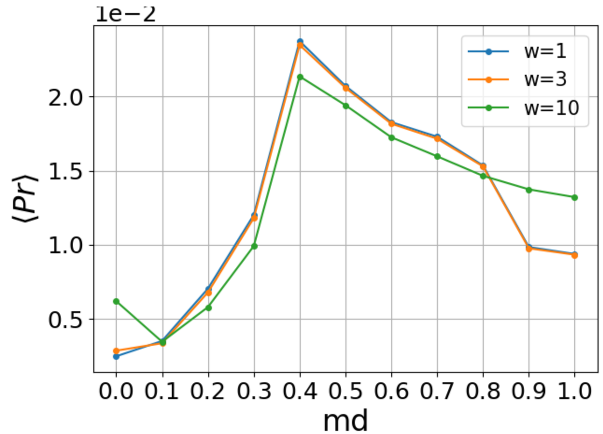
⇒ <Pr>, Spr and F display similar variation

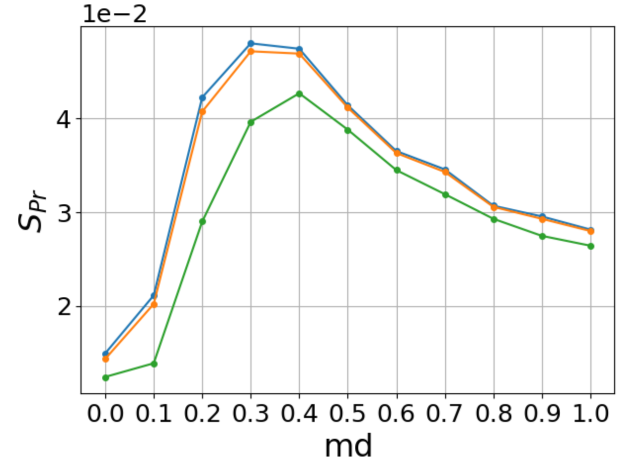
cristina.masoller@upc.edu @cristinamasoll1

Analysis of number of peaks, mean prominence and sum of prominences

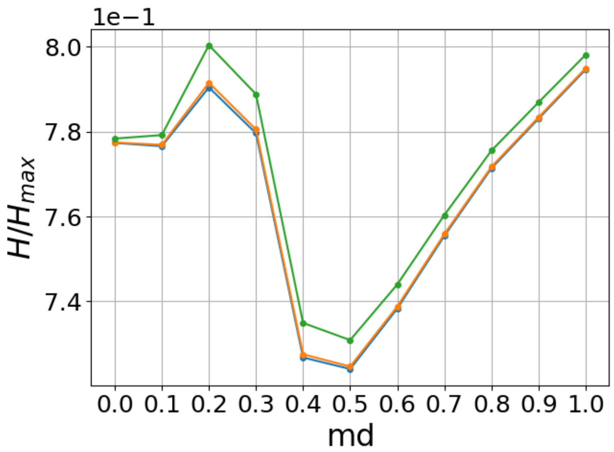
Numerical far field profiles

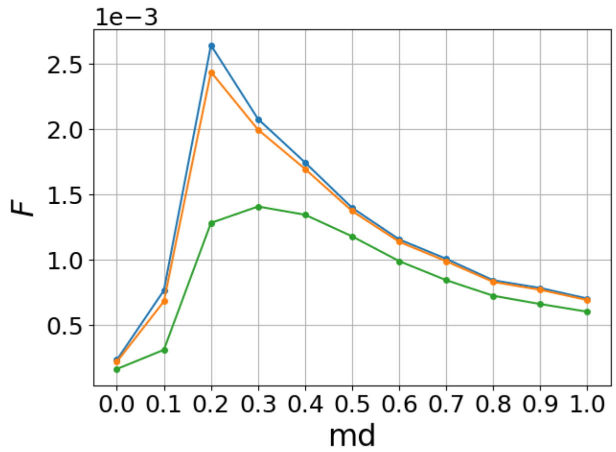






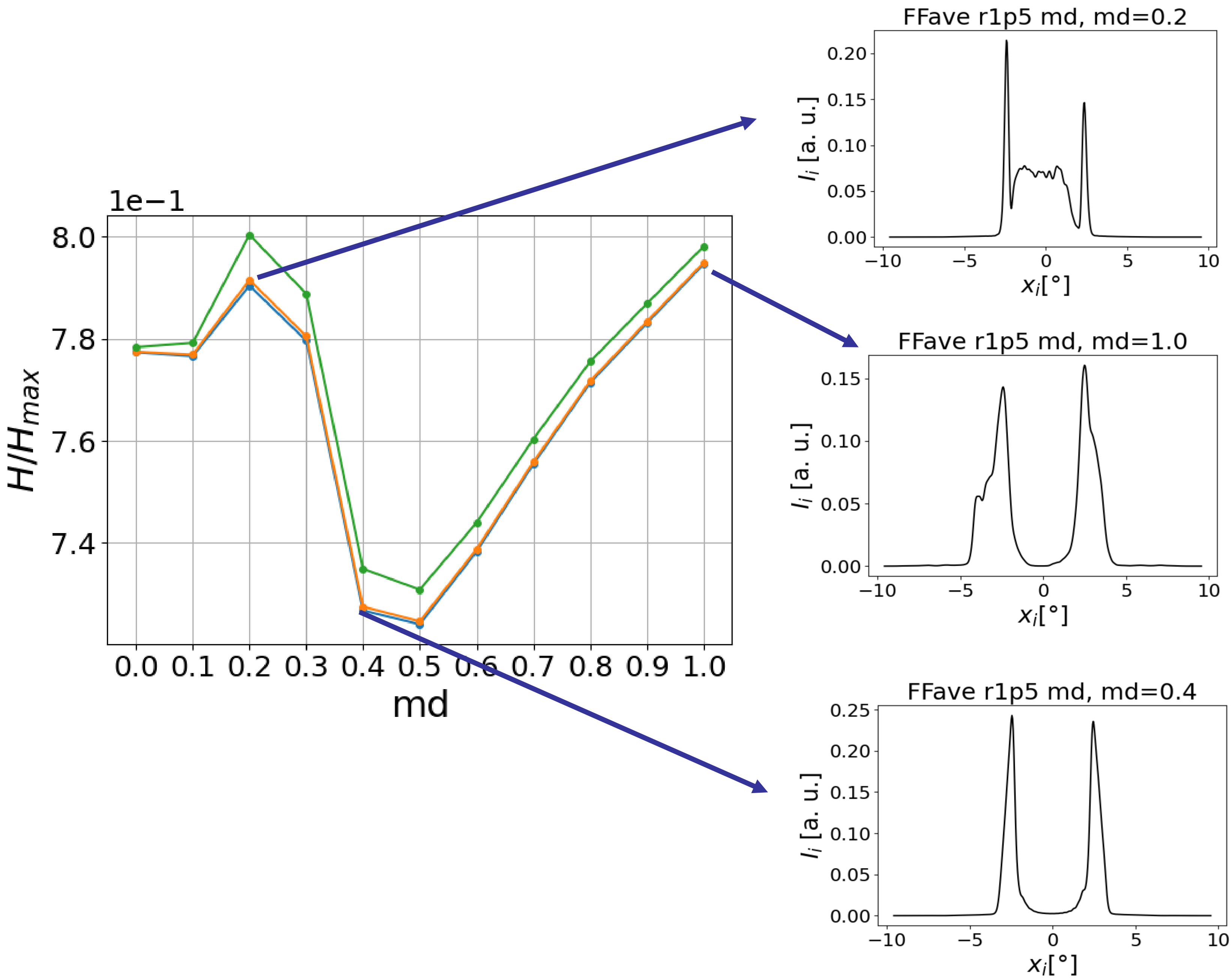
(Modulation amplitude)





<Pr>, Spr and F display similar variation
H more informative.

cristina.masoller@upc.edu @cristinamasoll1



cristina.masoller@upc.edu @cristinamasoll1

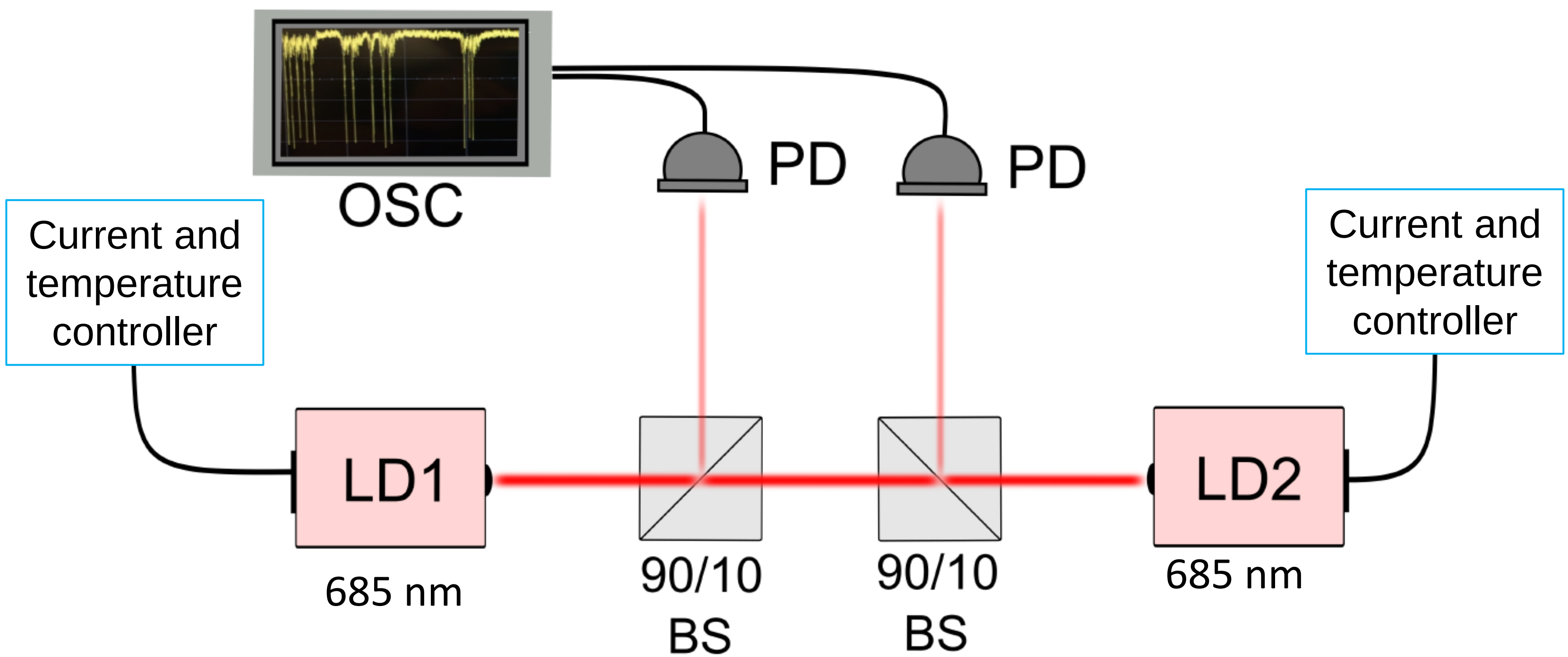
So far:
Developing metrics for quantifying spatial filamentation in broad area lasers.

Next:
Developing metrics for quantifying "spikiness" of the dynamics of edge emitting lasers.

cristina.masoller@upc.edu @cristinamasoll1

Motivation and research question

Experimental studies in our lab of two optically coupled semiconductor lasers, to implement "**photonic neurons**" for **spike-based** information processing and sensing.

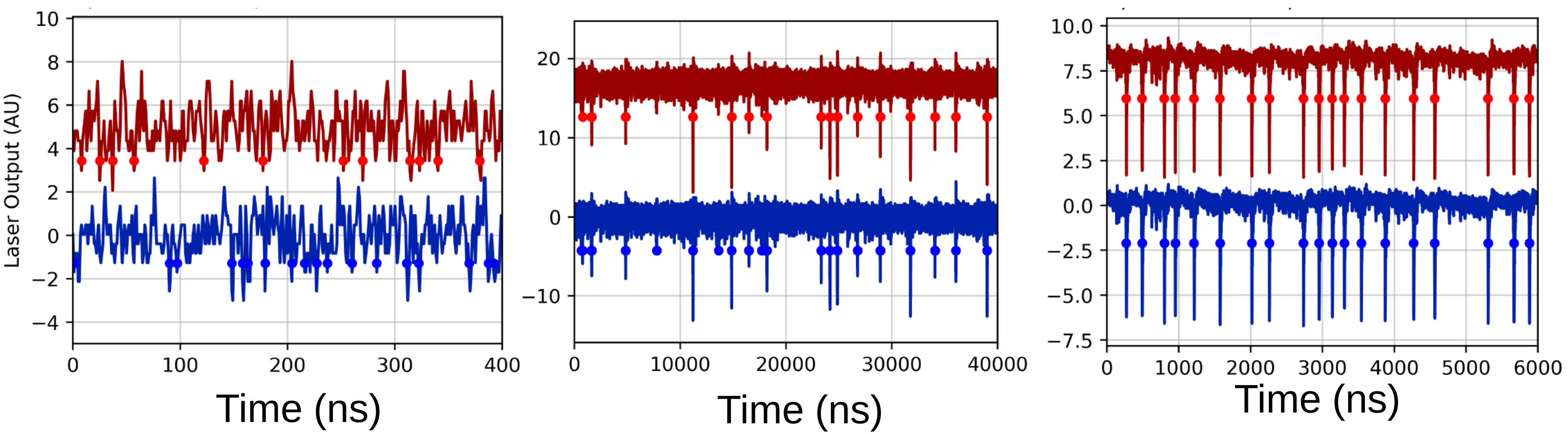


Information Processing and Sensing with Photonic Neurons.
European Office of Aerospace Research and Development (EOARD, FA8655-24-1-7022)

cristina.masoller@upc.edu @cristinamasoll1

Research question

Time series under different experimental conditions, normalized to zero-mean and unit variance and displaced vertically for clarity.



How to quantify the quality of the spikes?

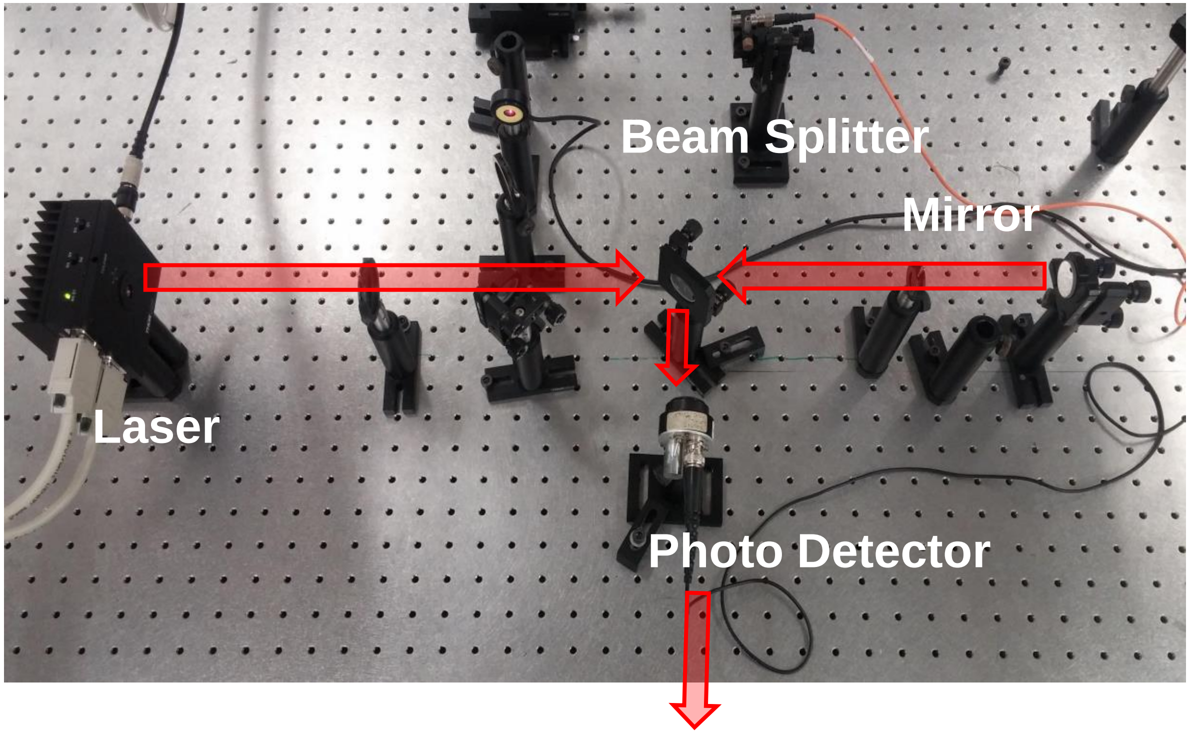
Information Processing and Sensing with Photonic Neurons.
European Office of Aerospace Research and Development (EOARD, FA8655-24-1-7022)

cristina.masoller@upc.edu @cristinamasoll1

Previous work in our lab on a related research question

Experiments with a semiconductor laser with optical feedback

How to identify the parameter region where the laser emits well-defined spikes?



Oscilloscope

What do we see in the oscilloscope?
(with 1 GHz resolution)

cristina.masoller@upc.edu @cristinamasoll1

Dynamics of the laser intensity when the pump current increases

Quantitative identification of dynamical transitions in a semiconductor laser with optical feedback

Carlos Quintero, Jordi Tiana-Alsina, Jordi Roma,
M. Carme Torrent, and Cristina Masoller.

Grup de Recerca en Dinàmica No Lineal, Òptica No Lineal i Làsers
UNIVERSITAT POLITÈCNICA DE CATALUNYA

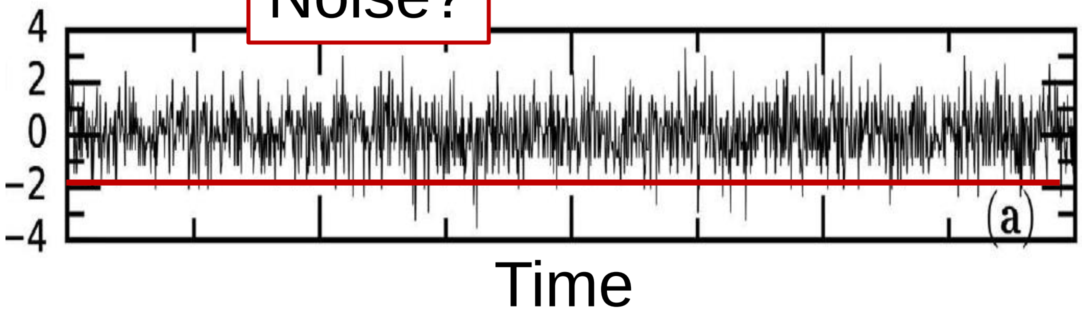
Dinàmica i Òptica No Lineal i Làsers (DONLL)
Dept. Física, Terrassa, Barcelona, Spain

cristina.masoller@upc.edu @cristinamasoll1

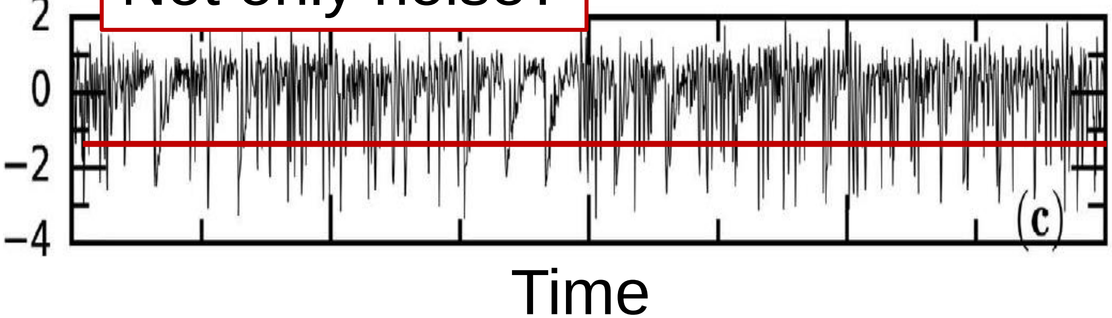
By counting the number of "threshold crossings", we can distinguish dynamical regimes

$$Z = \frac{X - \mu}{\sigma}$$

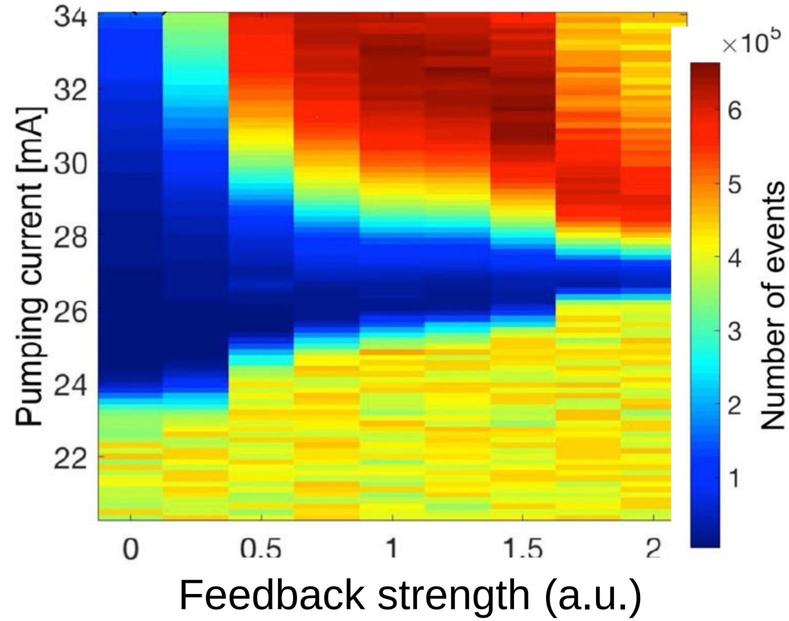
Noise?



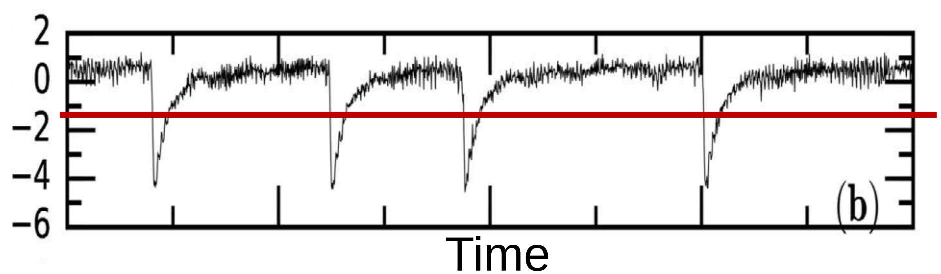
Not only noise?



Number of crossings below -1.5σ in log scale



Blue region? Optical Spikes



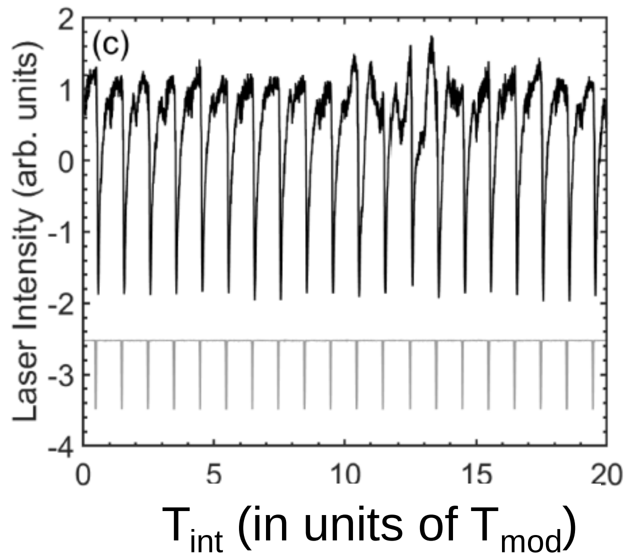
M. Panozzo, C. Quintero, J. Tiana-Alsina, M.C. Torrent, C. Masoller, Chaos 27, 114315 (2017).

cristina.masoller@upc.edu @cristinamasoll1

Small-amplitude current modulation: pulsed waveform

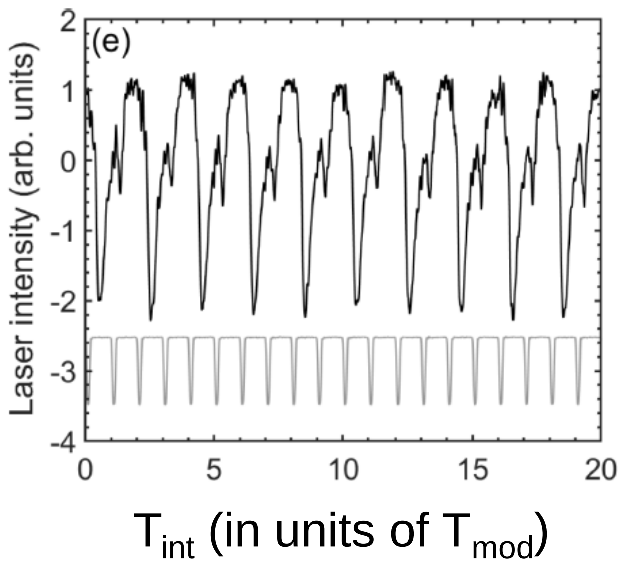
f_{mod}

5 MHz



1:1 locking

25 MHz



1:2 locking

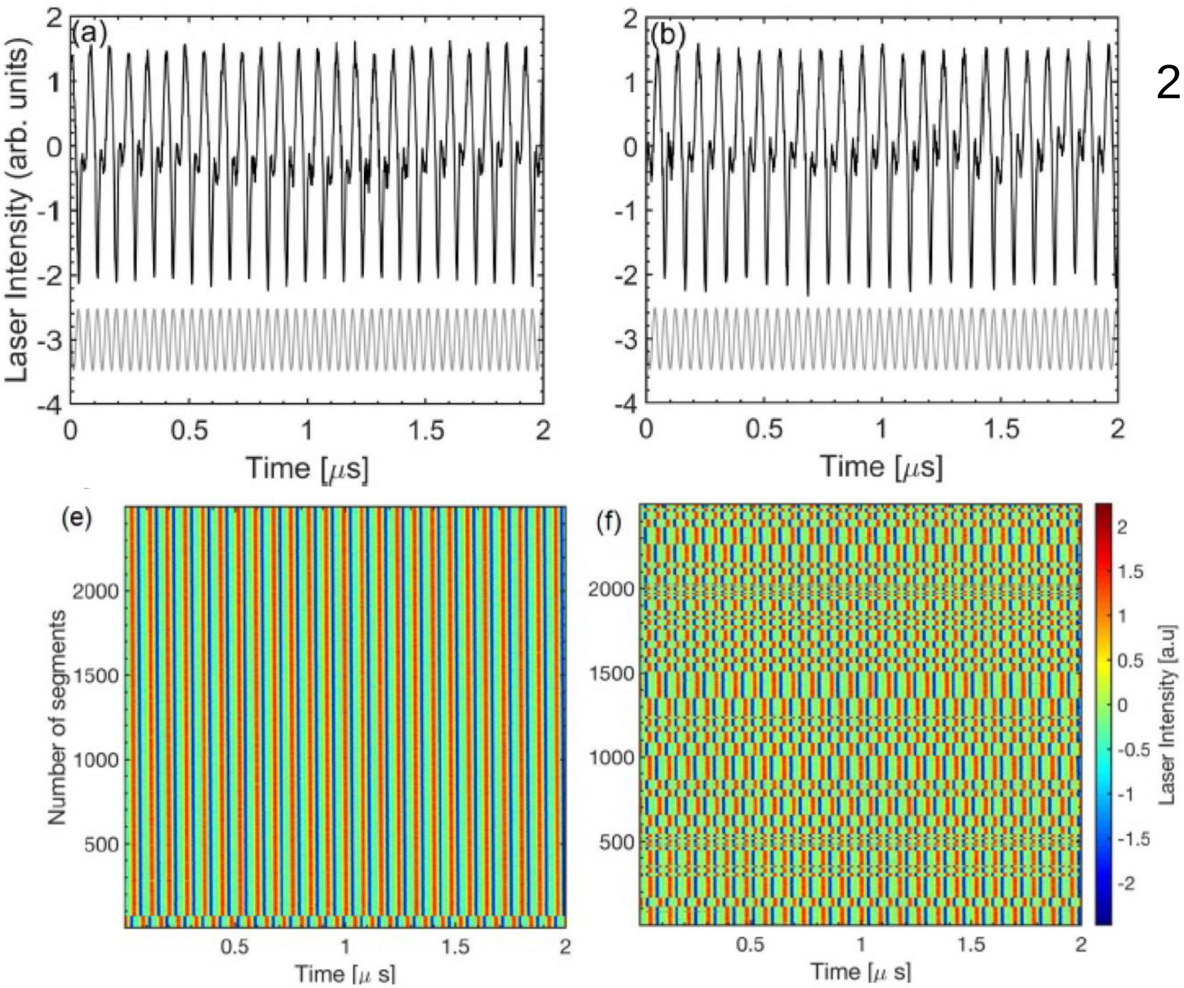
cristina.masoller@upc.edu @cristinamasoll1

Small-amplitude sinusoidal modulation

No 1:1 *regular* locking at low frequencies

25 MHz

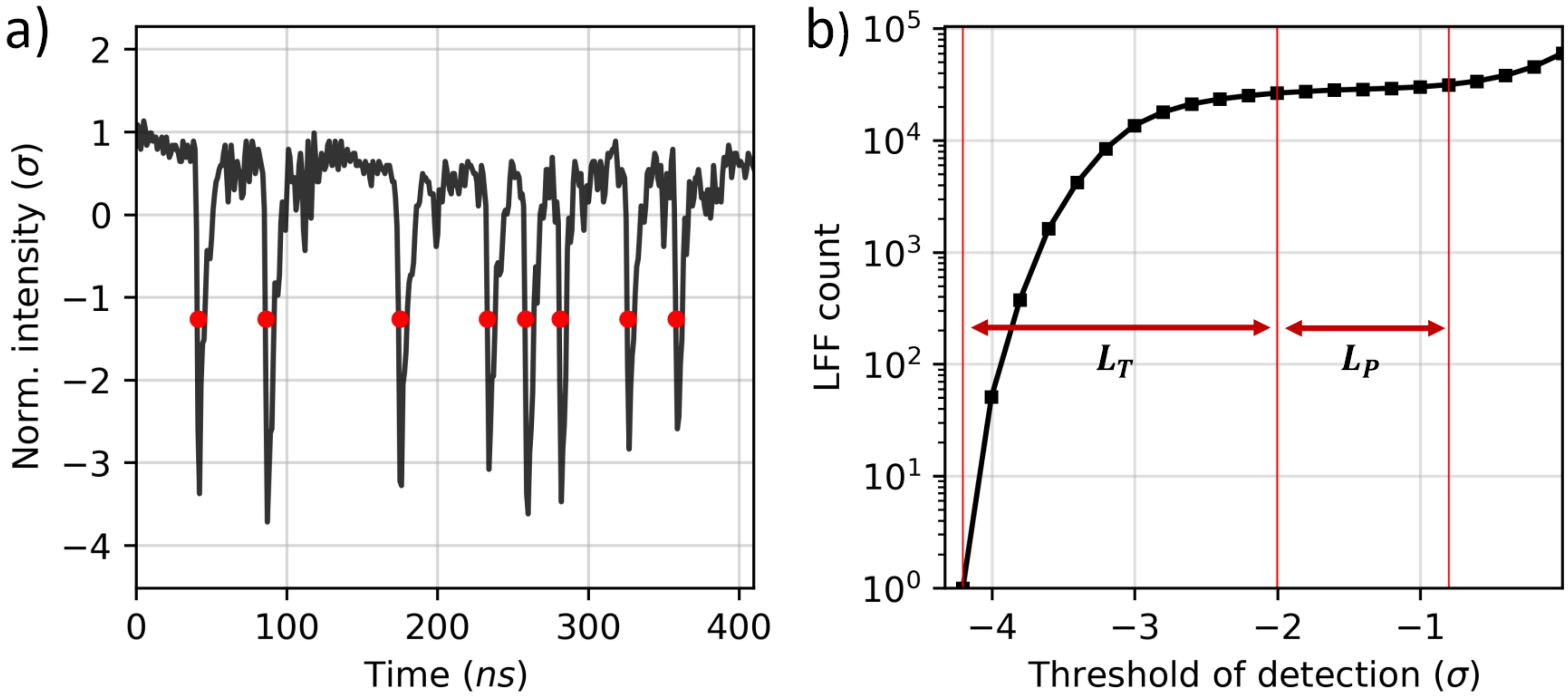
23 MHz



J. Tiana Alsina and C. Masoller, *Time crystal dynamics in a weakly modulated stochastic time delayed system*, Sci. Rep 12, 4914 (2022)

cristina.masoller@upc.edu @cristinamasoll1

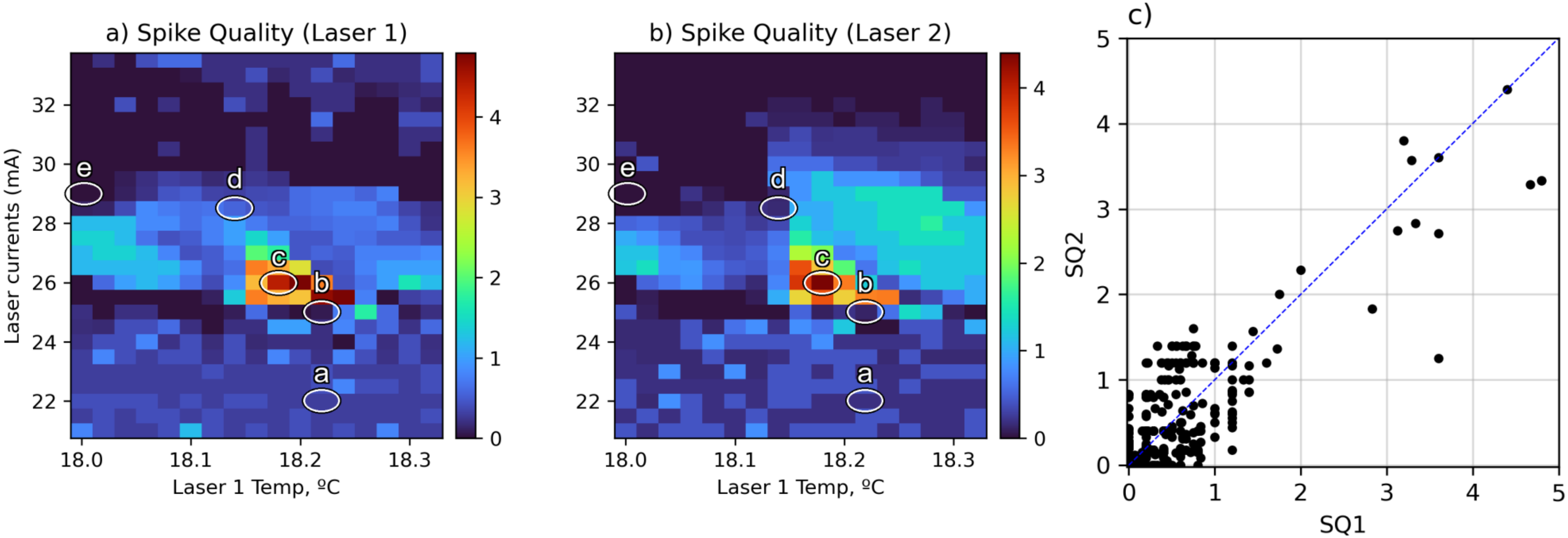
Spike quality quantification



$$\boxed{SQ = L_P / L_T}$$

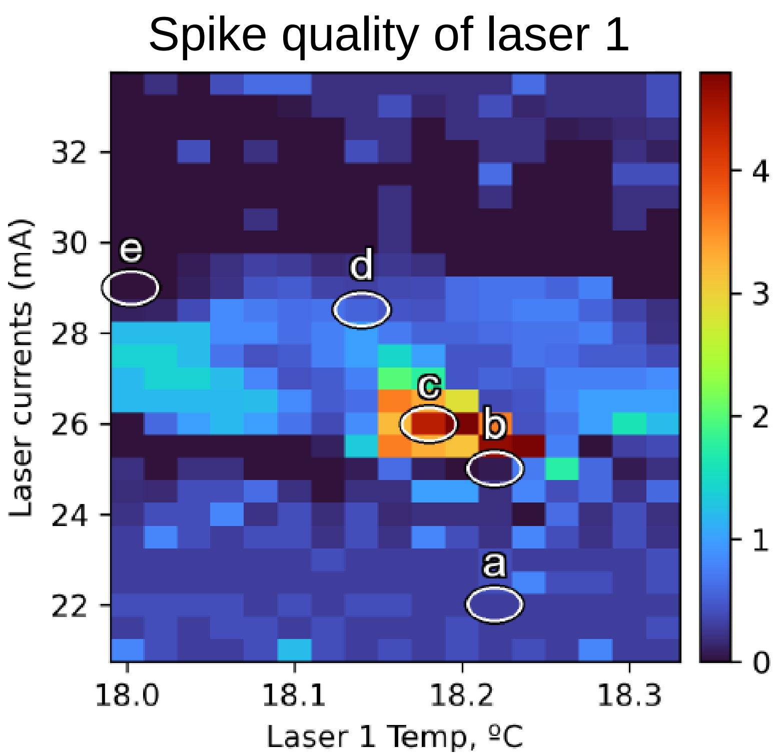
cristina.masoller@upc.edu @cristinamasoll1

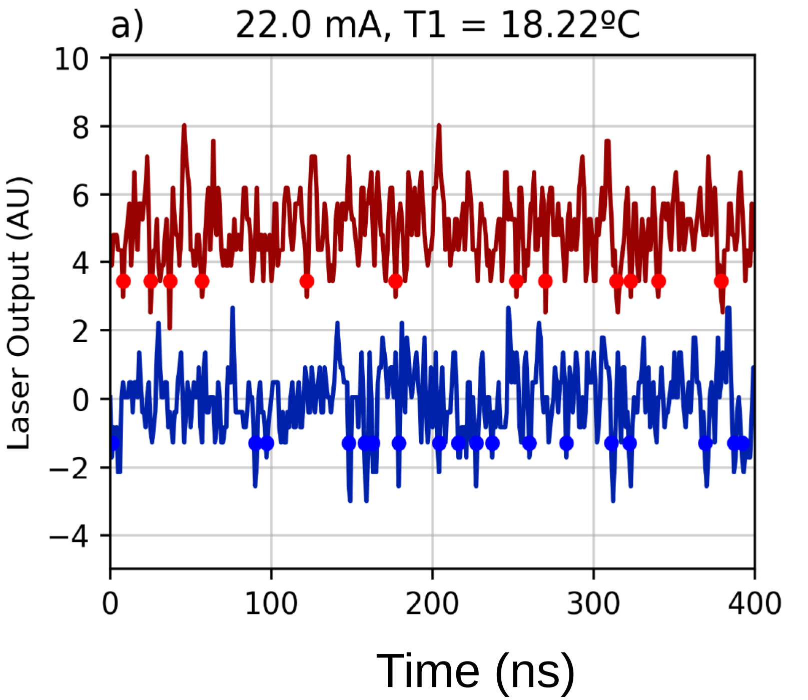
Results for two mutually coupled lasers

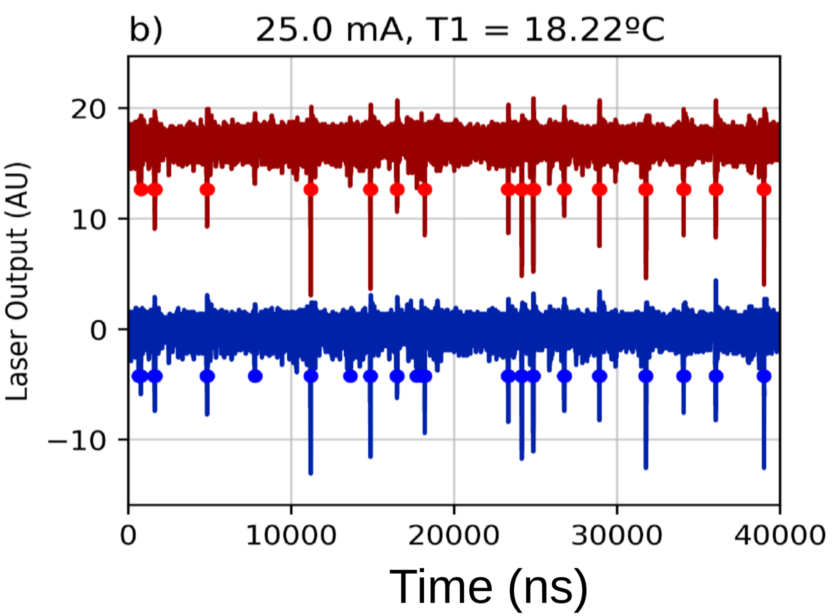


cristina.masoller@upc.edu @cristinamasoll1

Lasers’ dynamics in different regions of the parameter space

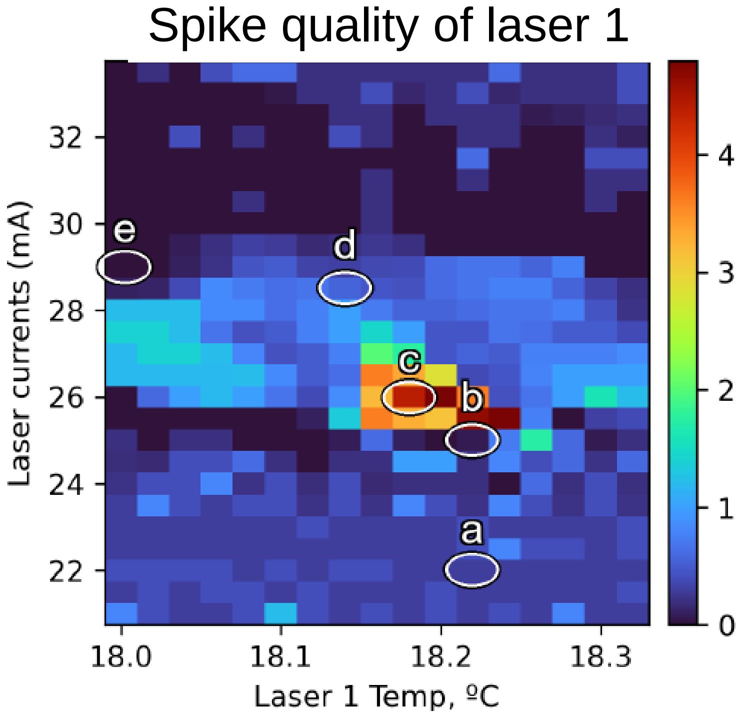


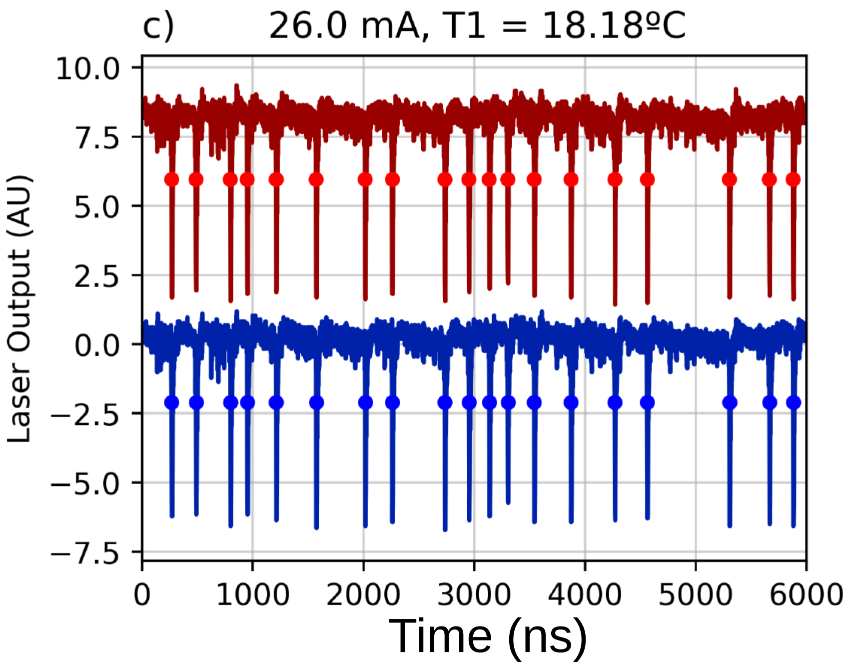


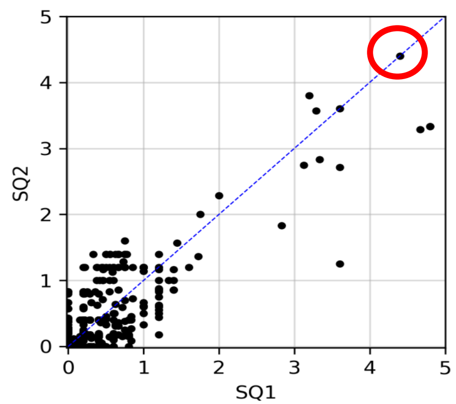


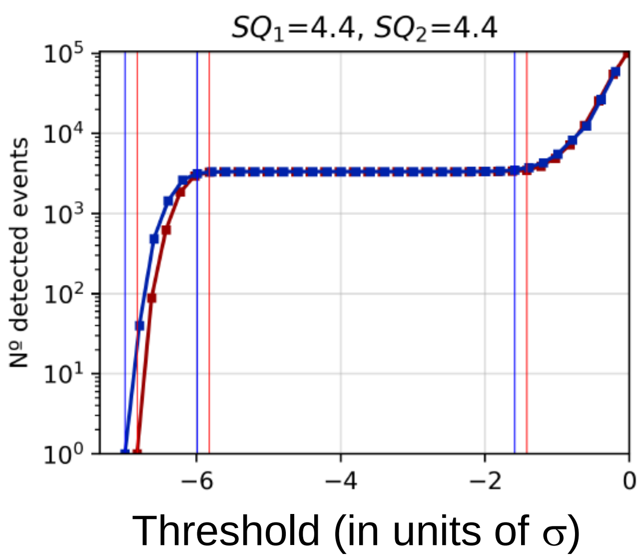
cristina.masoller@upc.edu @cristinamasoll1

Lasers' dynamics in different regions of the parameter space



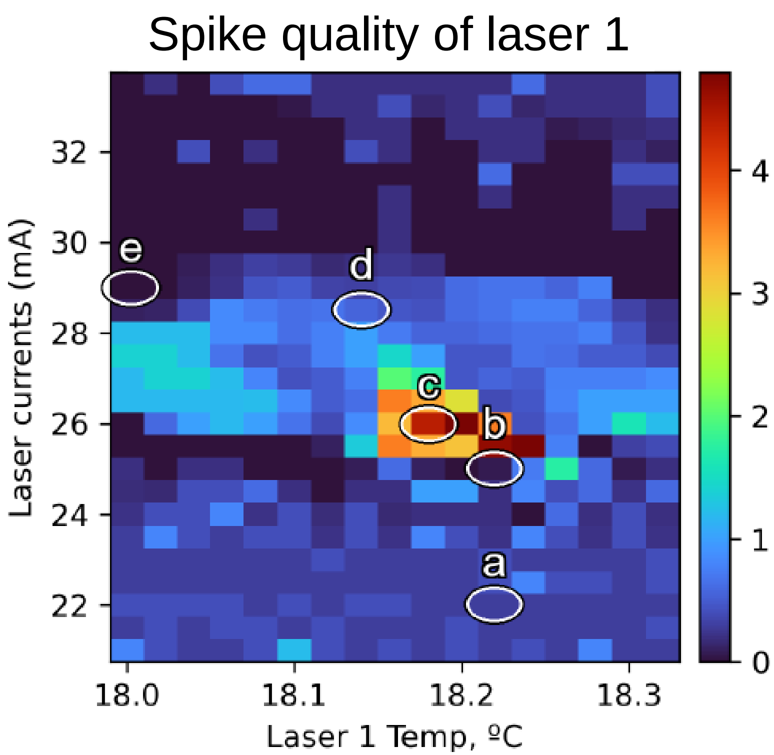


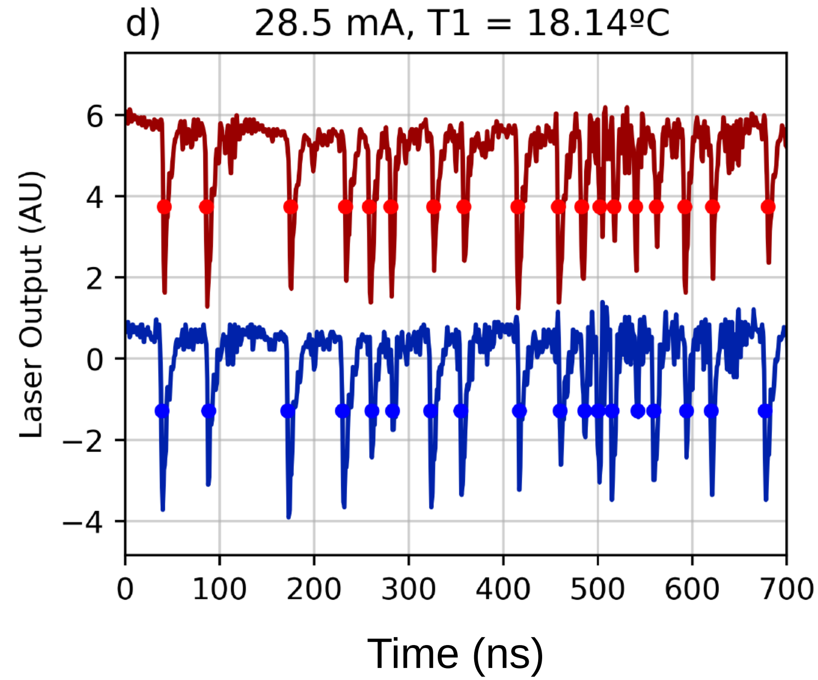


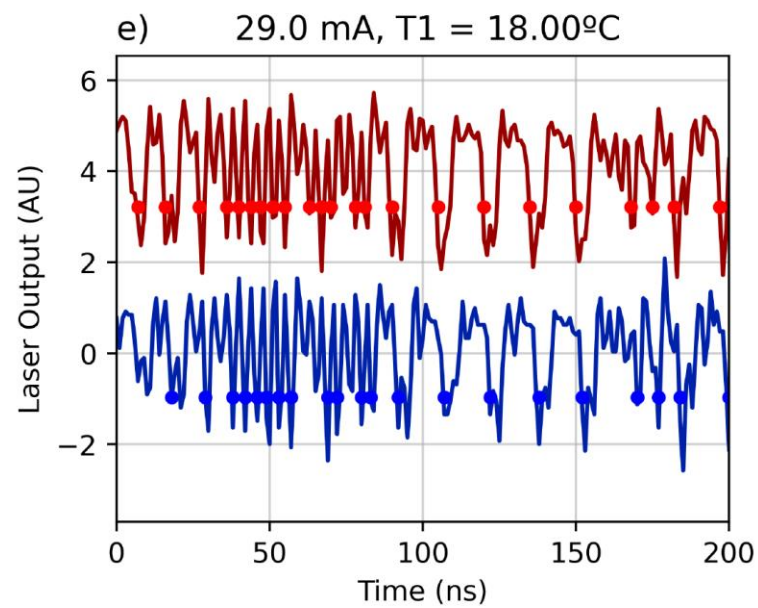


cristina.masoller@upc.edu @cristinamasoll1

Lasers' dynamics in different regions of the parameter space

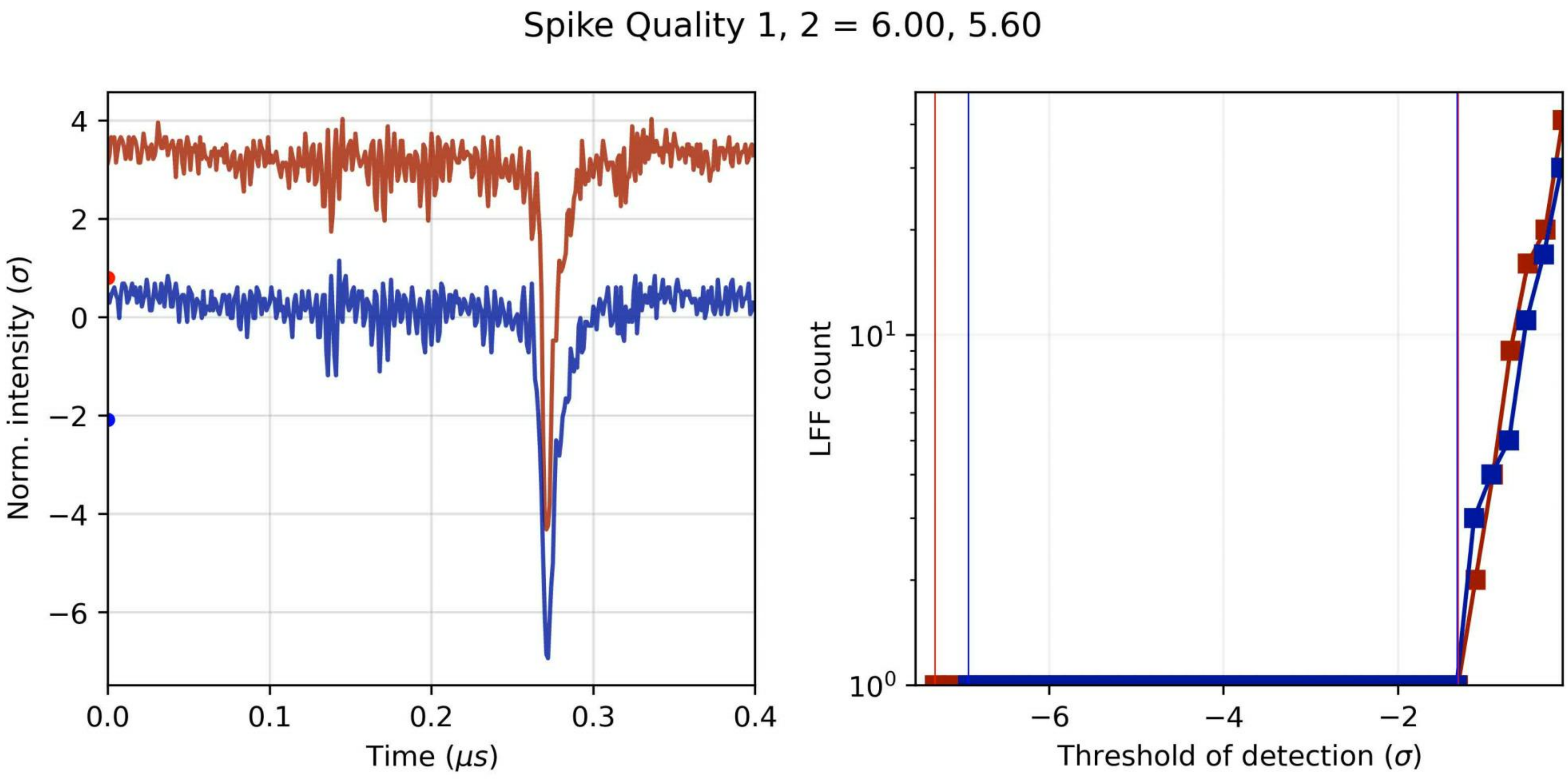






cristina.masoller@upc.edu @cristinamasoll1

How many spikes do we need to quantify the spike quality?



cristina.masoller@upc.edu @cristinamasoll1

Take home messages and future work

- Quantifying the spatial inhomogeneity of the laser beam
  - Fisher information (*F*) and Shannon entropy (*H*): parameter free
  - But *F* and *H* fail to differentiate profiles with or without filaments.
  - Ongoing work: complement *F* and *H* with measures based on the number and/or prominence of the peaks detected in the spatial profile.

- Quantifying the temporal spikiness of the laser dynamics
  - Spike quality measure proposed.
  - Parameters identified where two coupled lasers emit high-quality spikes.
  - Next step: Test spike-based information processing, by encoding a small-amplitude signal in the pump current of one of the lasers.

Thank you for your attention!

UPC
Càtedra Chip UPC
d'arquitectures avançades
i sistemes fotònics
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
AGAUR
Agència de Gestió d'Ajuts Universitaris i de Recerca