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Structural pattern extraction from asynchronous two-photon laser fault injection using spectral analysis

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Motivation (1/2)

- ❑ Pulsed laser testing is commonly used as an in-lab tool for Single-Event Effects sensitivity assesment & mapping
  - ❑ Among other applications: sensitivity pattern extraction for rate prediction

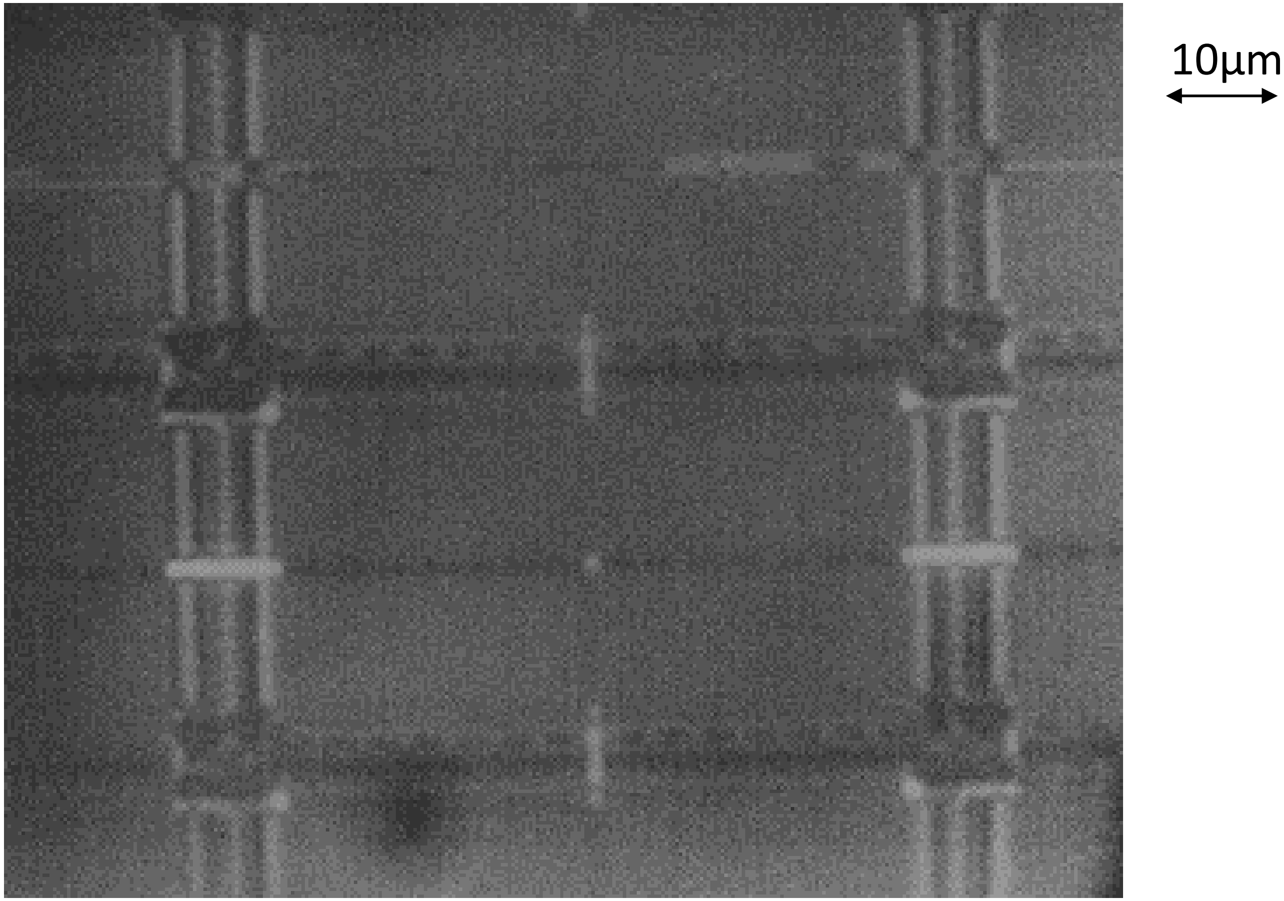
- ❑ Classical mapping approach:
  - ❑ Scanning + data acquisition
  - ❑ 1 (x,y) point ⇔ 1 pixel of the mapping ⇔ 1 measurement

- ❑ As most optical microscope-based techniques, laser testing of recent technologies is particularly demanding in terms of mechanical stability

- ❑ In a noisy environment, mapping repeatability can be challenging
  - ❑ Ex: Fan on the testboard, unstable air-cond., roadworks, wind in higher floors…

Motivation (2/2)

- Typical vibrations induced by fan on the testboard



- This work: extracting structural information without mapping

Outline

❑ Device under test & set-up

❑ Testing method

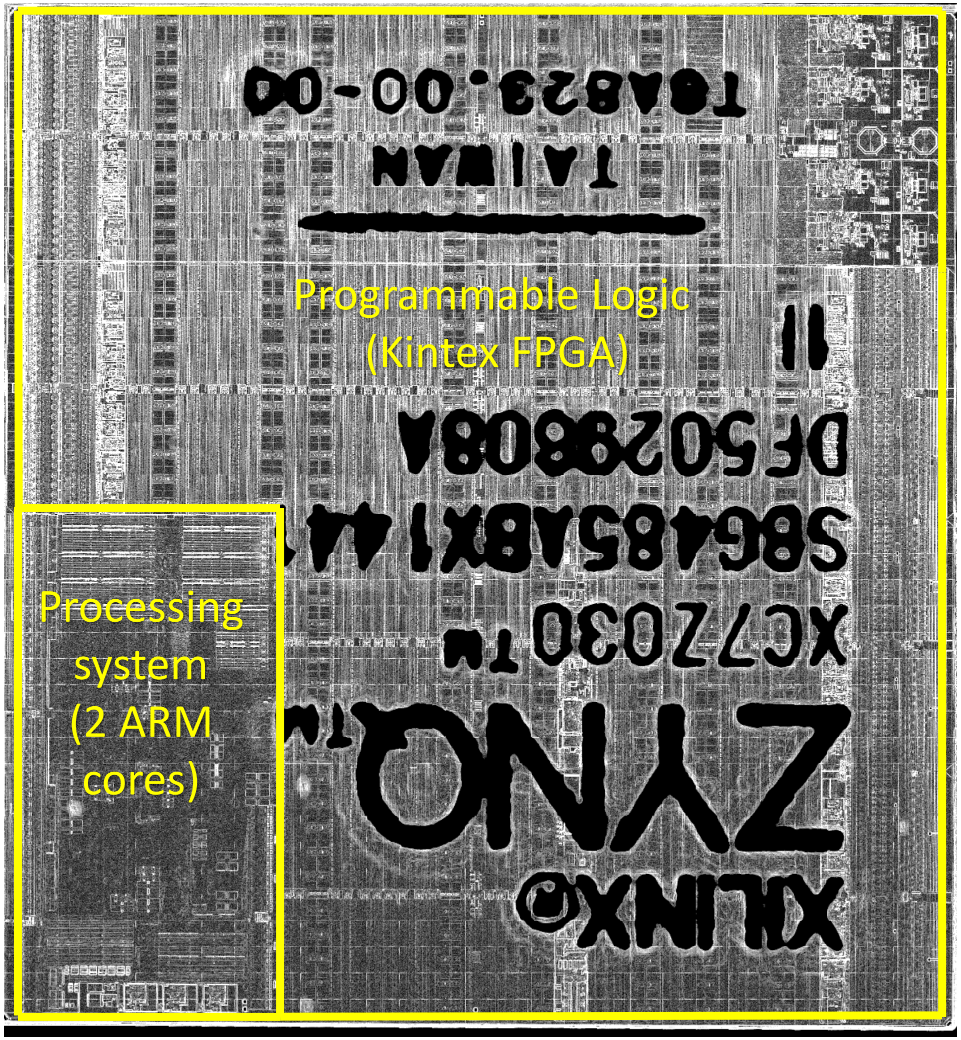
❑ Experimental results

❑ Simulation

❑ Conclusions

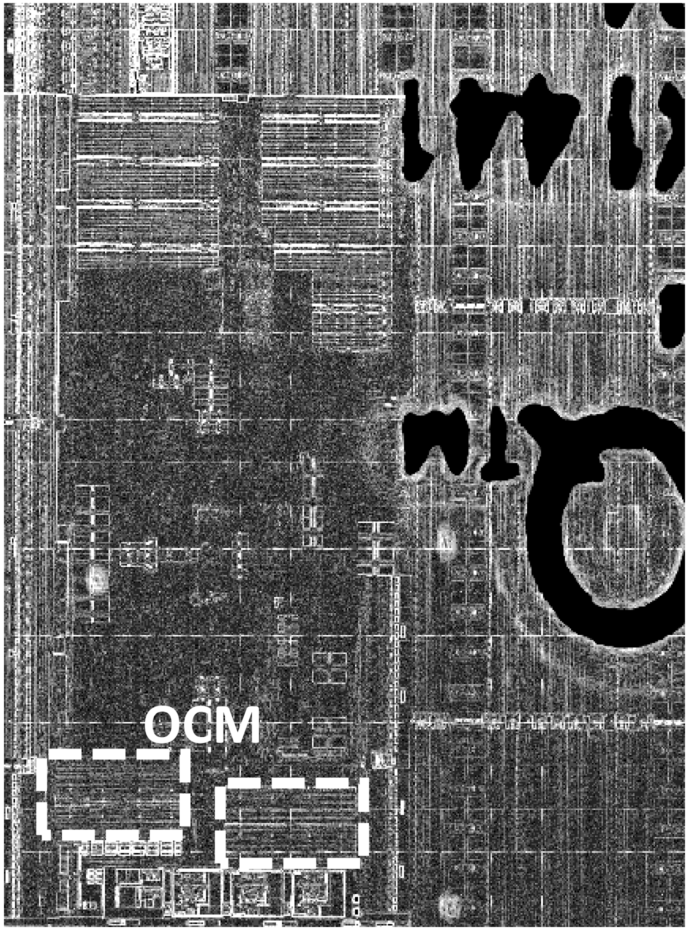
Device under test

- ☐ XC7Z030 ZYNQ 7000 Programmable System on Chip (SoC)
  - ☐ TSMC HKMG 28nm CMOS process
  - ☐ Flip-chip lid-less package version provides easy access to the die backside
  - ☐ Substrate thickness: 700µm



Region of interest

- ❑ On-chip memory (OCM)
  - ❑ 256KB SRAM
  - ❑ Shareable by both cores
- ❑ Critical section from a radiation-hardness assurance point of view when:
  - ❑ Used for cores synchronization
  - ❑ Used for software-level hardening
- ❑ Knowledge of the sensitive pattern required for event rate prediction



Laser testing set-up

- Two-photon absorption (TPA) microscope at IES
  - All-fiber laser source
  - Wavelength: 1.55µm
  - Femtosecond pulses
  - Infrared imaging system

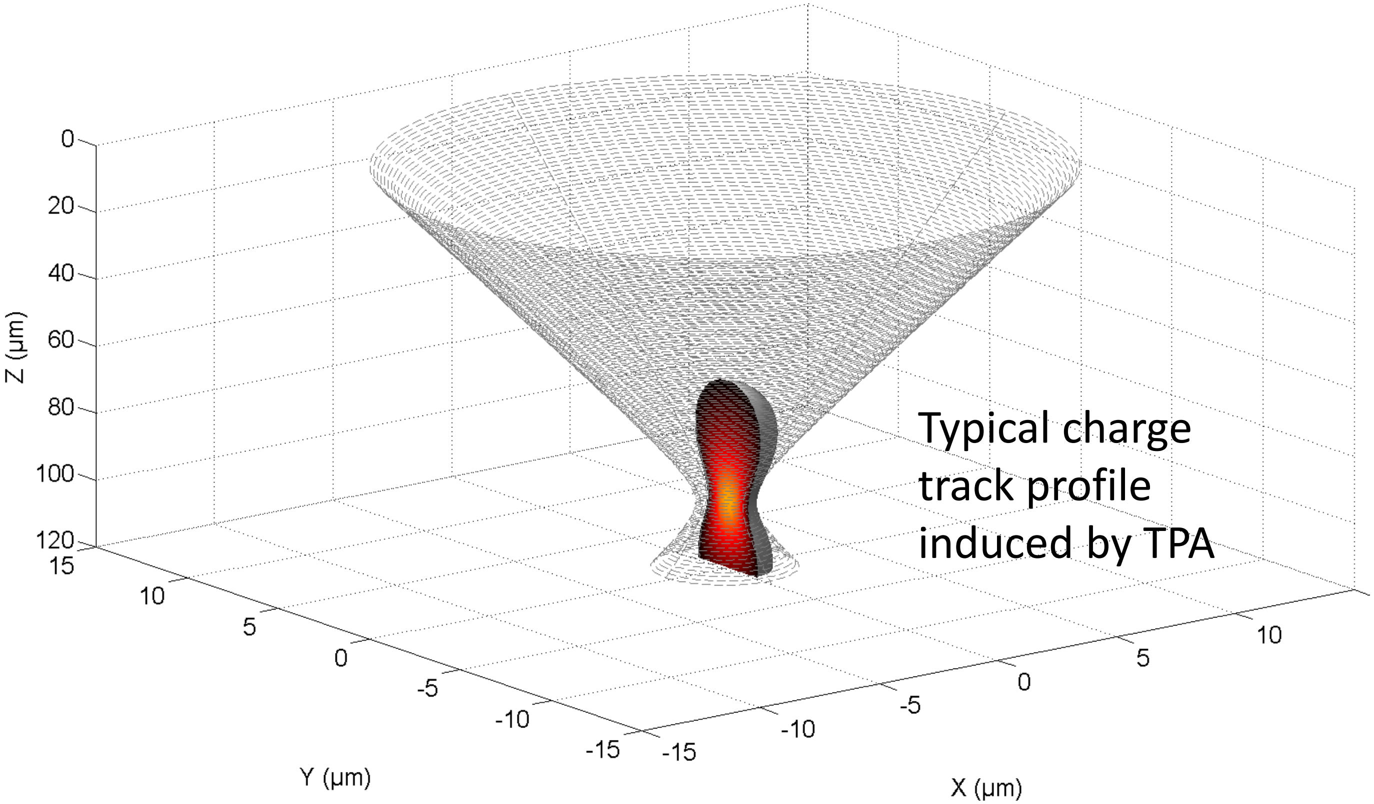
DUT testing method

- Self testing strategy
  - Real-time test software operates on one of the CPU cores
  - The program initiates, then periodically reads the OCM, report & correct errors
  - The program instructions and data are stored in an external memory
    - Test program not impacted by errors in the OCM

- Asynchronous testing
  - No synchronization between laser pulses, scanning motion and test loop
  - Test loop period: $T_S = 150ms$
    - Not affected by errors detection and reporting
  - Laser pulse period: $T_L = T_S + \varepsilon$
    - At most one laser pulse per test cycle => no false Multiple Cell Upset
    - Laser arrival time in the cycle different for each pulse = time-domain scan
    - Periodically, one test cycle without laser
      - Beating period: $T_B = T_L T_S/(T_L-T_S)$

Reminder: TPA-induced charge profile

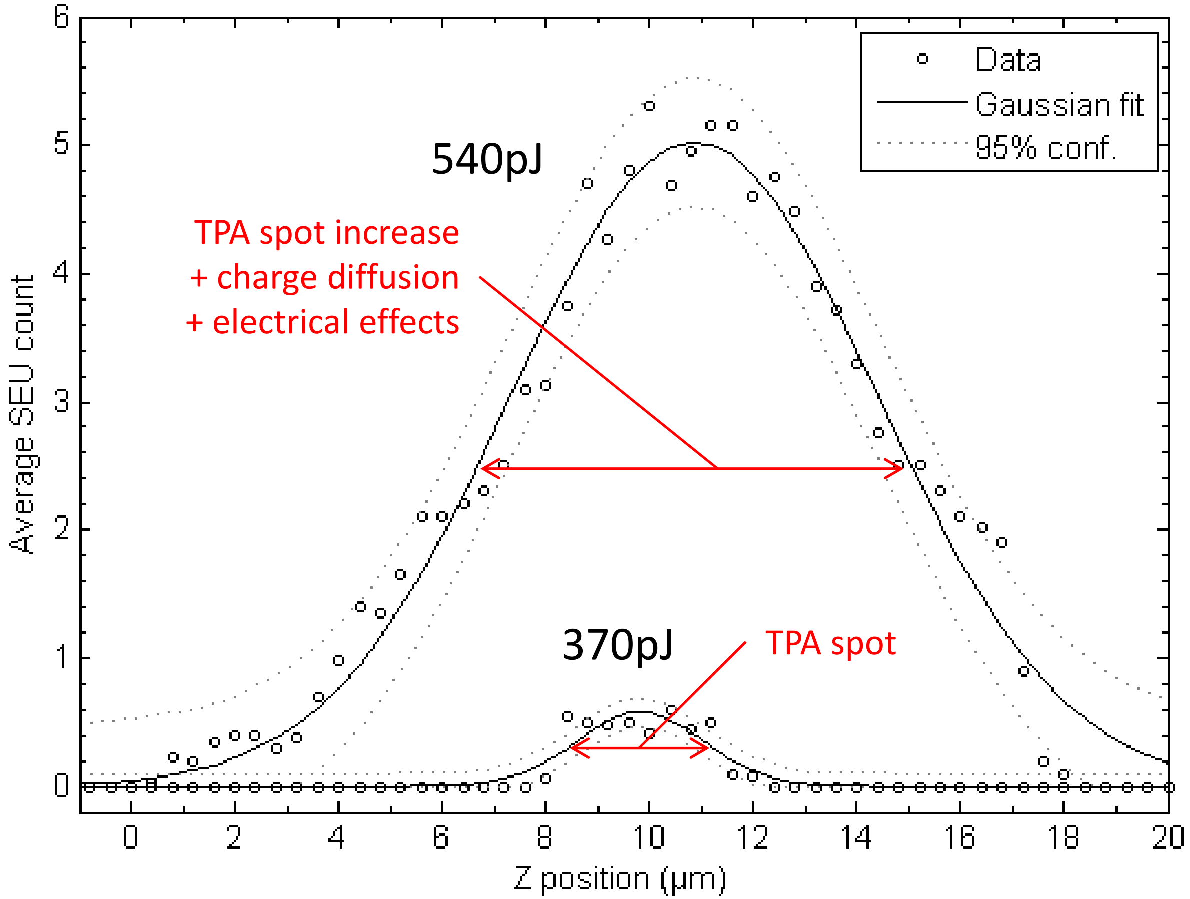
- ❑ Limited extension of the charge track along the optical axis
- ❑ Non-linear propagation effects in thick substrate
- ❑ Wavelength different from imaging wavelength
- ❑ => Offset between imaging focus and optimal laser focus



Typical charge track profile induced by TPA

First steps: define optimal Energy and Focus

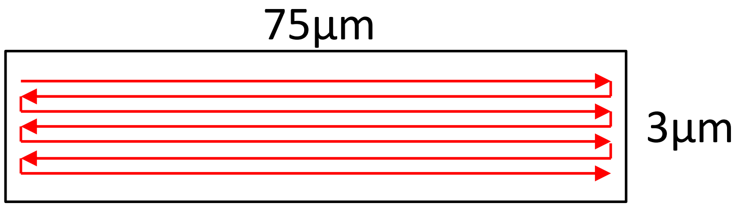
- ❑ Depth scan
  - ❑ Counting errors vs Z position, for different energies



- ❑ In the following: constant energy of 500pJ (tolerance to focus variations)

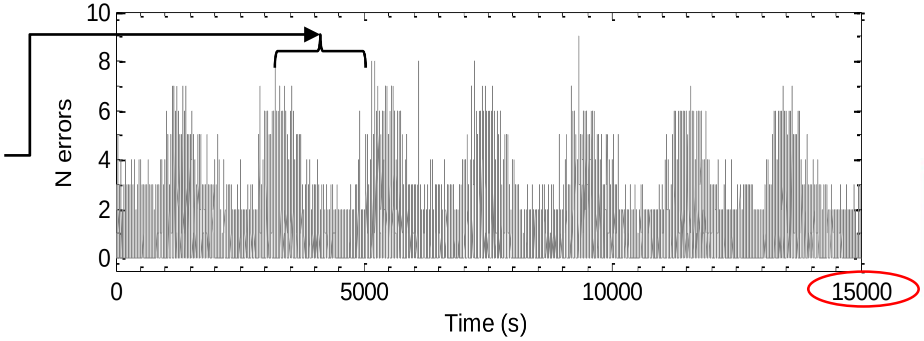
2D scan of an area in the OCM

- ❑ Area with high X/Y ratio
  - ❑ Continuous slow scan along X
  - ❑ 100nm steps along Y
- ❑ Scan repeated in a loop
  - ❑ Logging the number of errors detected in each test cycle



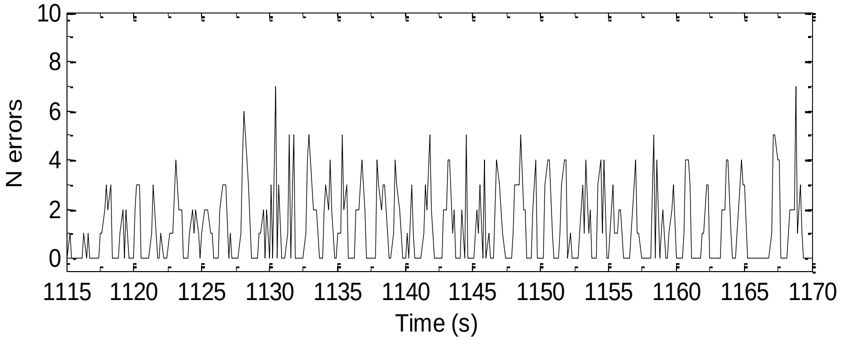
Long time scale:

Scan loop period clearly identified



Short time scale:

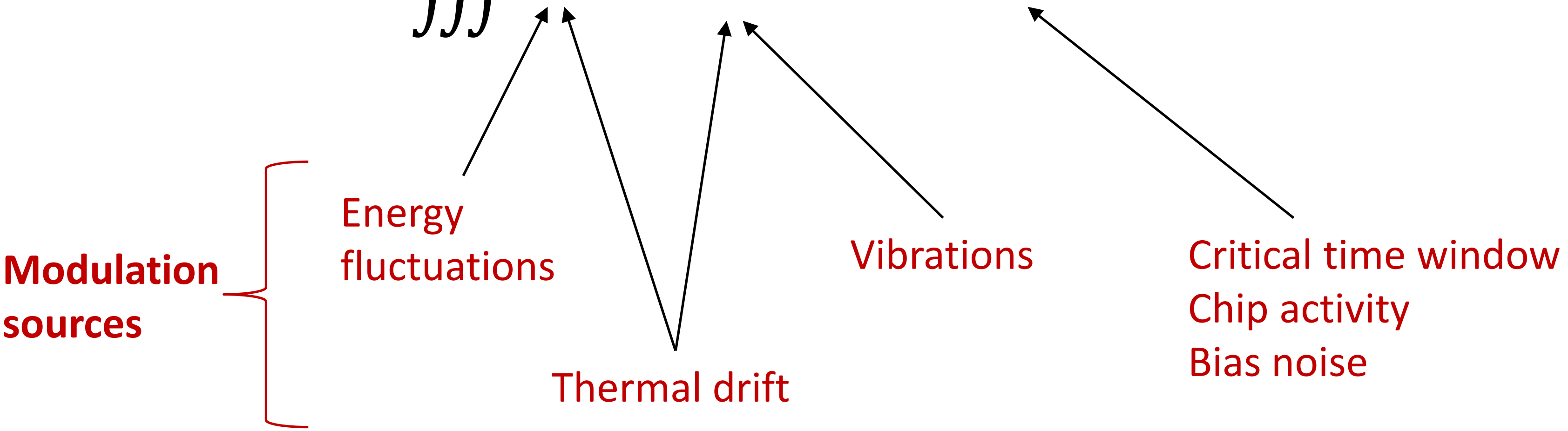
Noisy « signal »



Error signal & noise sources

- ❑ Error signal
  - ❑ Described by the convolution of laser charge profile with DUT sensitivity pattern

$$\overbrace{S(t)}^{\text{Error signal}} \propto \iiint \overbrace{L(\boldsymbol{r}-\boldsymbol{r}_L,\tau-t)}^{\text{Laser profile}}\,\overbrace{P(\boldsymbol{r},\tau)}^{\text{Sensitivity pattern}}\,d\tau\,d\boldsymbol{r}$$



Modulation sources

Energy fluctuations

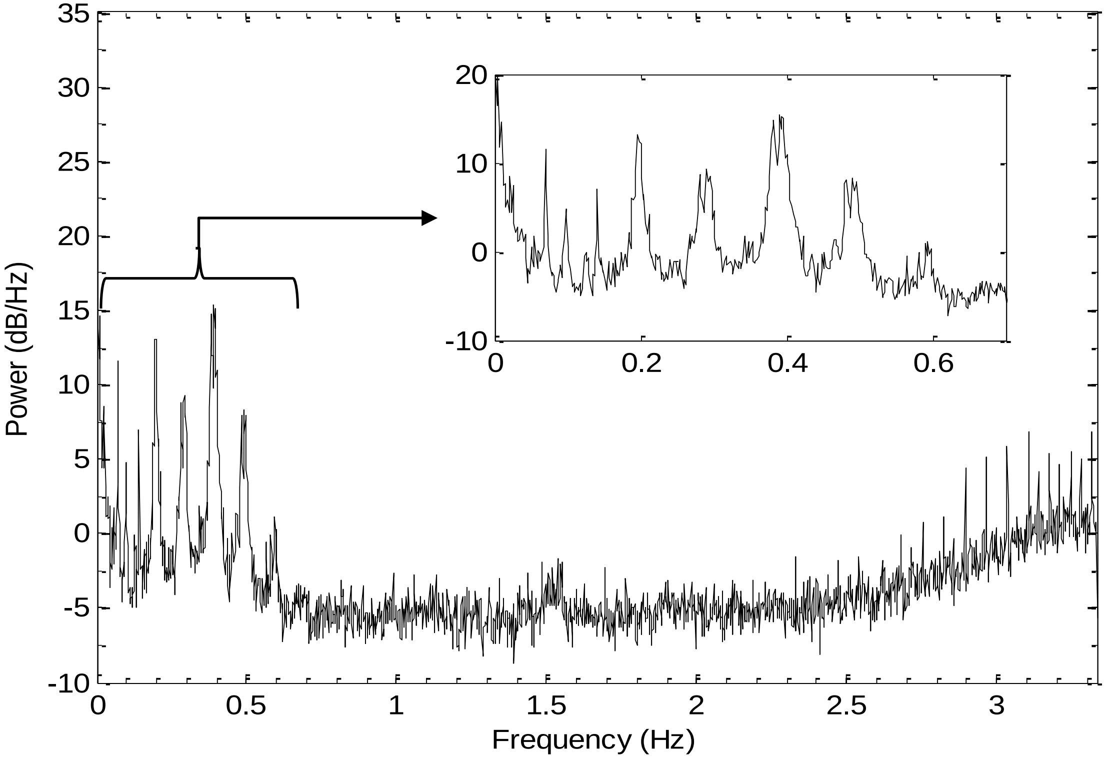
Thermal drift

Vibrations

Critical time window
Chip activity
Bias noise

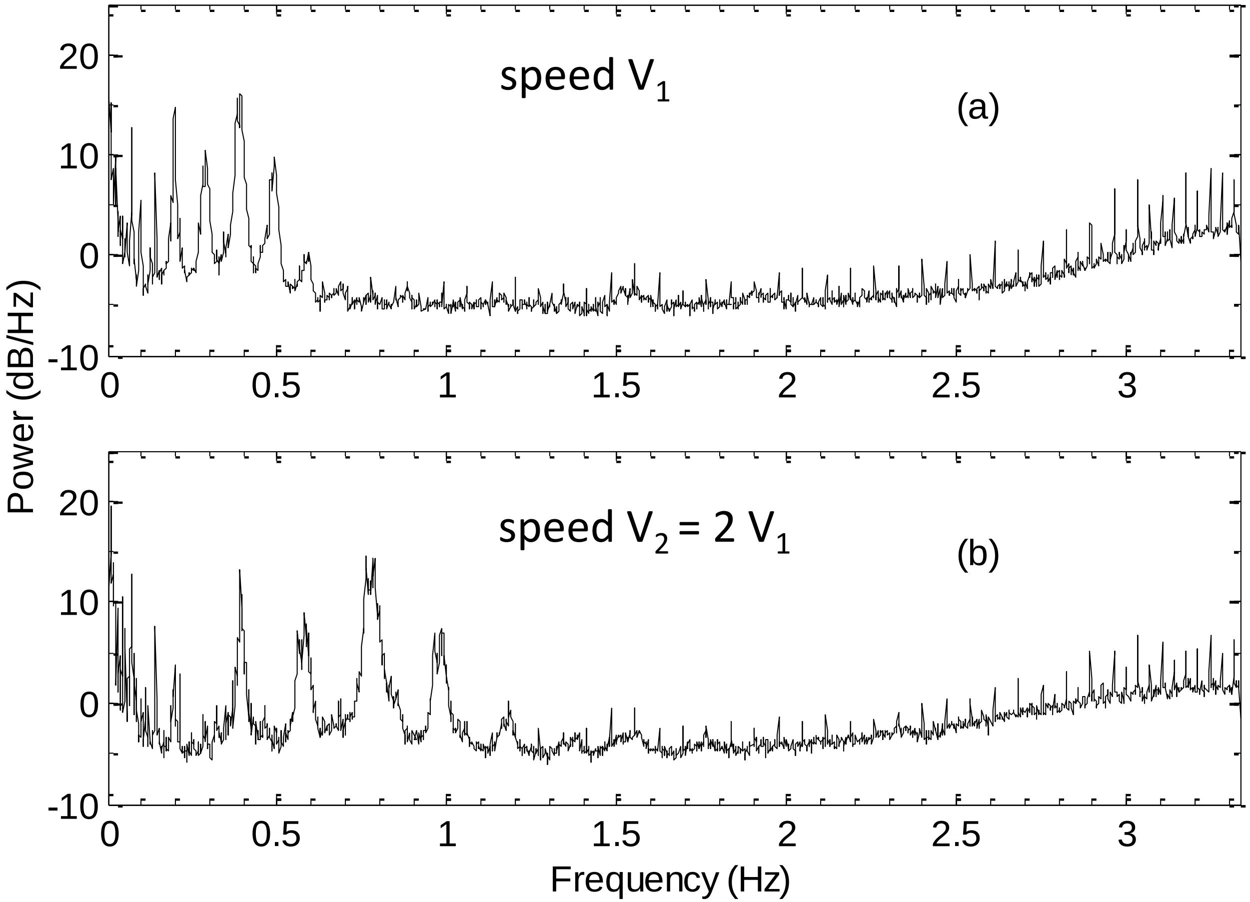
⇒ **Analysis in the frequency domain**

Error signal in the frequency domain



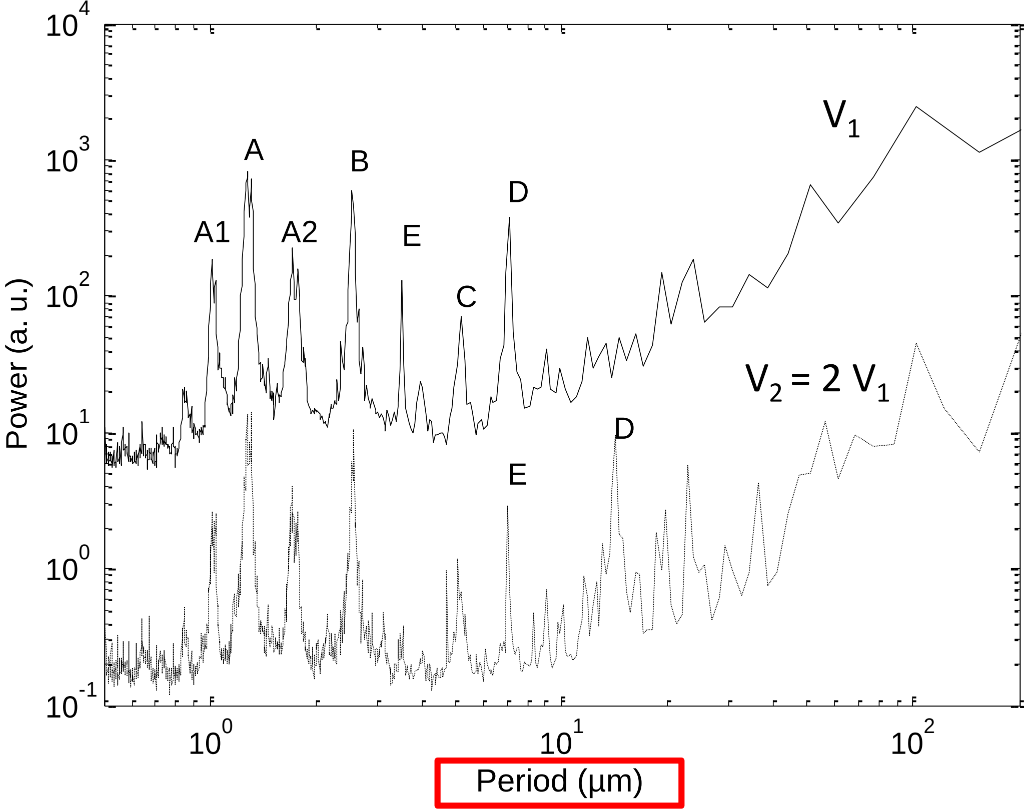
- ❑ Several strong peaks
  - ❑ Can some of them be related to a repetitive structure in the DUT ?
- ❑ How to distinguish between time-domain and space-domain modulations ?
  - ❑ ⇒ Repeat the same scan at a different speed

Scanning at 2 different speeds



- ☐ Peaks at same freq. = time-domain modulations
- ☐ Peaks at twice the freq. = space-domain modulations = DUT structural pattern
  - ☐ What are the corresponding dimensions ?

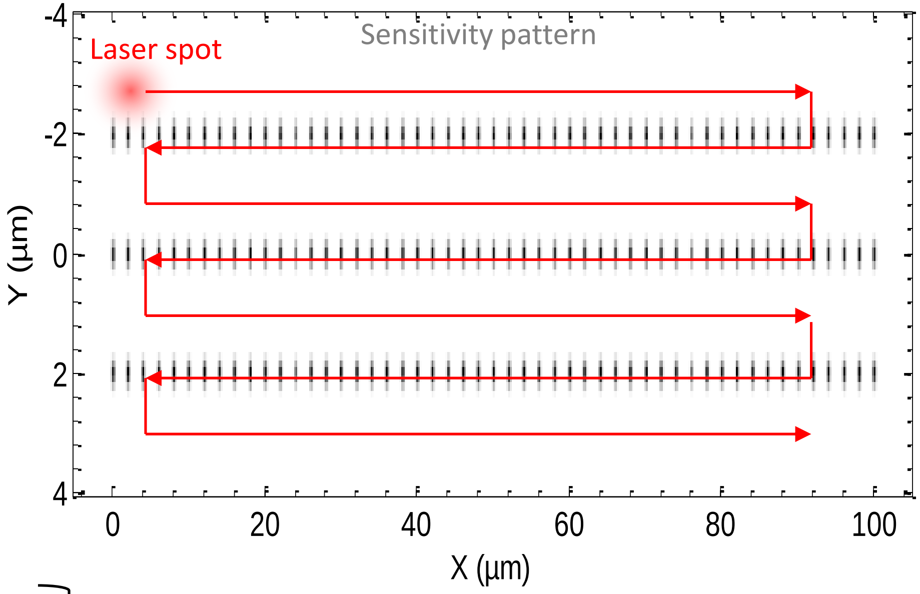
Plotting the results vs spatial period



- ❑ Convert frequencies into spatial periods using P = V / f
- ❑ Peaks at same period = DUT structural pattern
- ❑ Peak A = **1.25µm**
  - ❑ **Subwavelength pattern resolved from vibrations without any DUT synchronization**

Modelling of the experiment

- Calculating the dynamic convolution of the laser charge track with a 2D sensitivity pattern

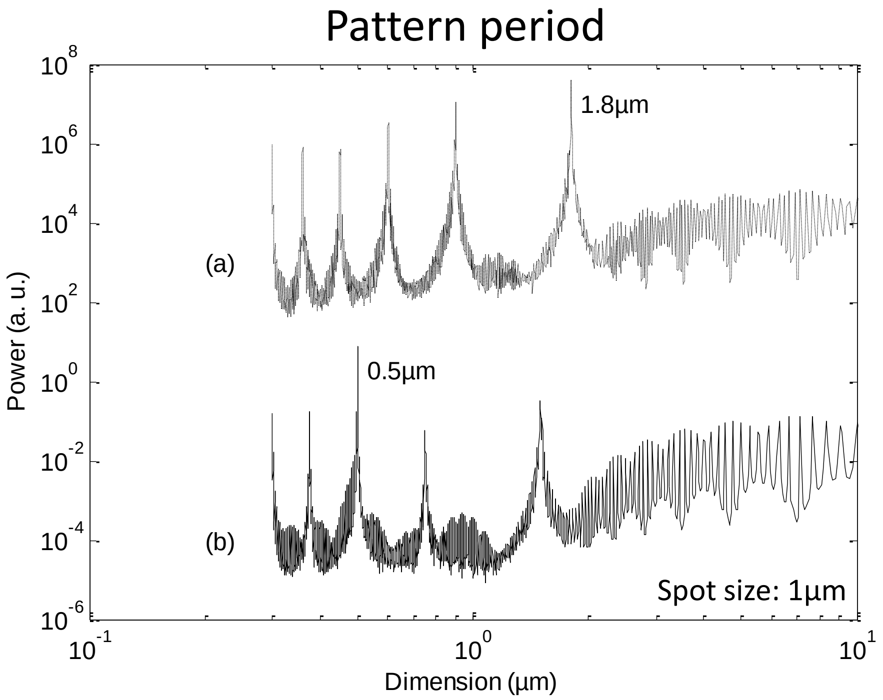


- Using a simple critical charge model for event generation
- Including every time-related aspect of the experiment
  - Scanning speed
  - Laser pulse frequency
  - Real-time test loop for event detection
- Including various noise sources

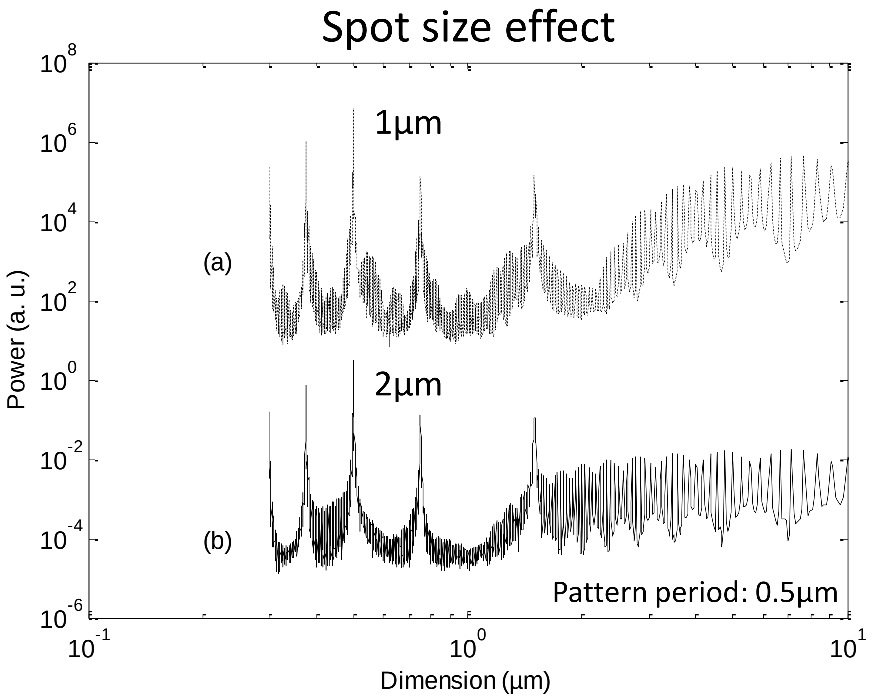
Model output:
Error signal **vs time**

- Allows for quick estimation of the influence of experimental parameters

Modelling results



Pattern period



Spot size effect

- Minimum detectable pattern: $d_{min} = 2 V T_S$

- Pattern resolution not limited by spot size
  - No significant effect of the spot size on the spectrum

Conclusions

- ☐ Structural (sensitivity) pattern extraction from pulsed laser fault injection using slow scan and frequency-domain analysis of the error logs
- ☐ No synchronization required between laser, scanning and test equipment
- ☐ Sub-spot size and sub-wavelength periods extracted despite vibrations and multiple noise sources
- ☐ Accurate modelling of the scan timings shows limited effect of the spot size on the resolution
  - ☐ Resolution limited by speed, test loop period and detection mechanism (charge diffusion)
- ☐ Possible applications
  - ☐ Radiation effects: SEE sensitive pattern extraction
  - ☐ Security: reverse engineering for laser-based attacks
  - ☐ Failure analysis: pulsed laser stimulation techniques
- ☐ Future work
  - ☐ Working closer to the energy threshold to improve resolution
  - ☐ Automate spectrum processing to reconstruct more complex patterns (1D → 2D)