INVESTIGATION OF MECHANICAL PROPERTIES OF ORTHOPAEDIC TITANIUM ALLOYS BY ACOUSTIC EMISSION MONITORING

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PRESENTATION CONTENTS

- Small acoustic emission system based on USB oscilloscope
  - *- types of USB streaming oscilloscopes*
  - *- Matlab monitoring code with GUI*
  - *- peak amplitudes estimation for fast RMS and CNT evaluation*
- Experimental testing of of Ti-Mo-Si alloys
  - *- demo audio monitoring of recorded signals*
  - *- comparison of acoustic emission activity depending on Si percentage*
  - *- spectral analysis of detected AE hits*
  - *- factor analysis of recorded signal types*

General principles and terms of AE

Acoustic Emission (AE) - elastic waves propagating trough the material as a result of *dynamic relaxation of mechanic stress* inside a material or a process affecting the *emergence of elastic stress waves on the body surface*.

AE Method - *detection* of AE signal from ***ACTIVE*** defects, *electronical signal processing* and following *parameter evaluation* of detected AE signal.

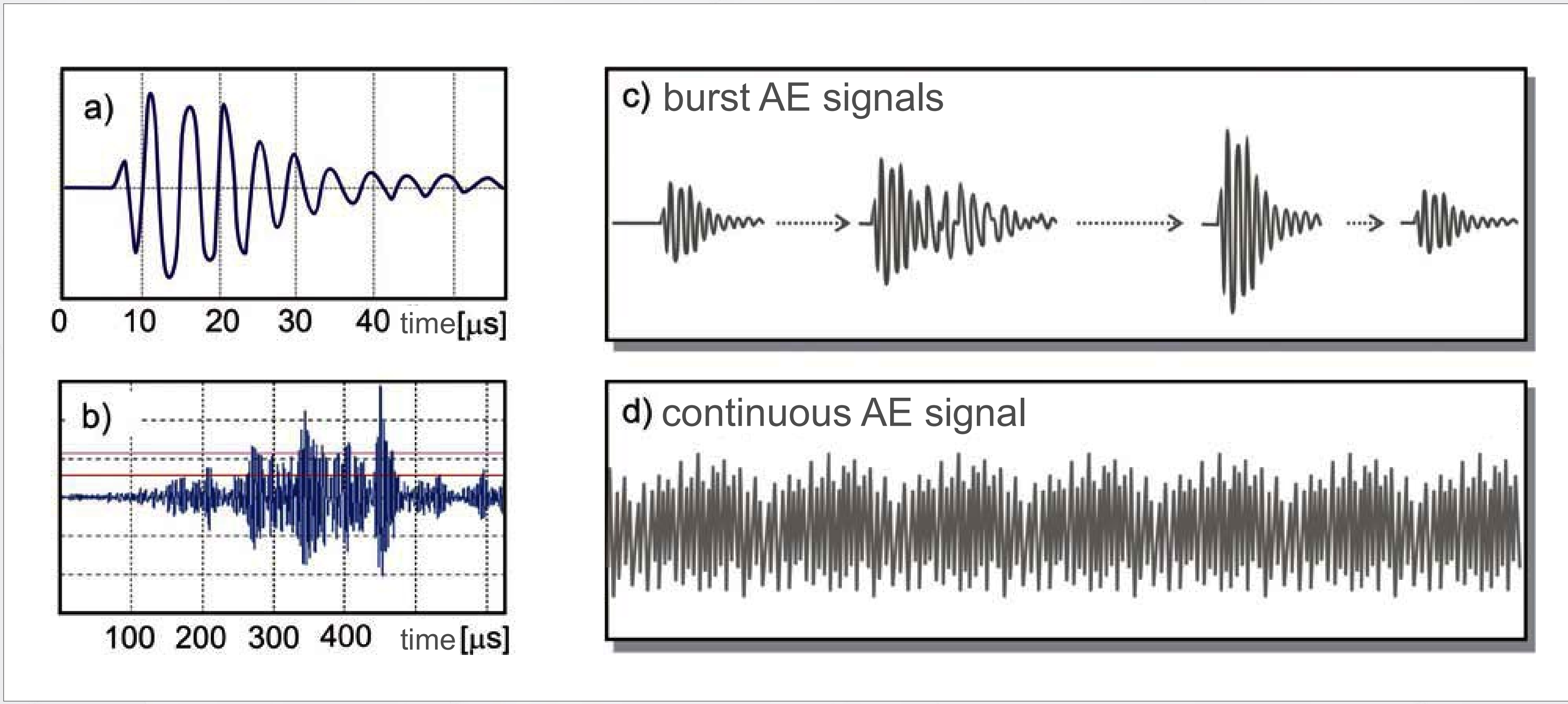
AE inception - *deformation* or a *violation of structural integrity* of solid.

Elastic stress waves in bodies are analogical to acoustic waves propagating trough the air. Audible sound is carried by the waves of air pressure changes. Waves in solids are propagating by elastic deformations and stresses proceeding trough the body. After reaching the material surface, these are converted to electrical signal by piezoceramic sensors, digitized and analyzed by PC.

Analogy: *earthquake and tsunami.*

ACOUSTIC EMISSION MONITORING

burst or *continuous* ?



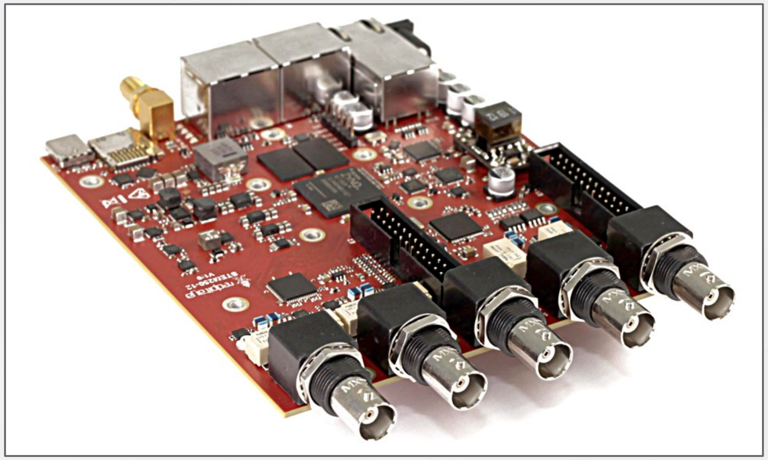
Burst AE: *plastic deformation of metals, crack growth, friction, material failure...*

Continuous AE: *leakage of liquids under pressure, machining, welding, monitoring of technological processes and devices...*

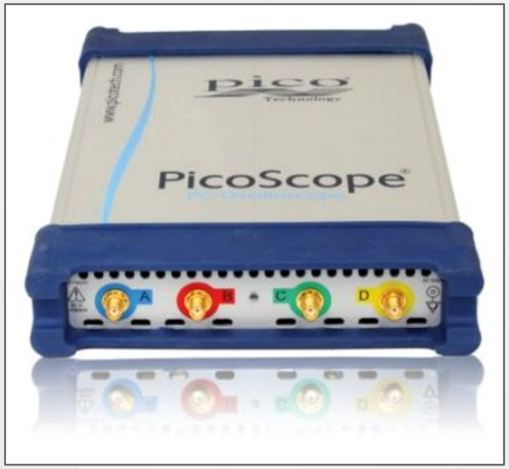
CONTEMPORARY LABORATORY HARDWARE

*PC-controlled data **streaming** oscilloscopes*

Red Pitaya STEMlab 250-12: *250 MHz, 12 bits*



PicoScope 6407: *1 GHz, 8 bits*



Cleverscope CS448: *50 MHz, 14 bits*

SMALL ACOUSTIC EMISSION SYSTEM

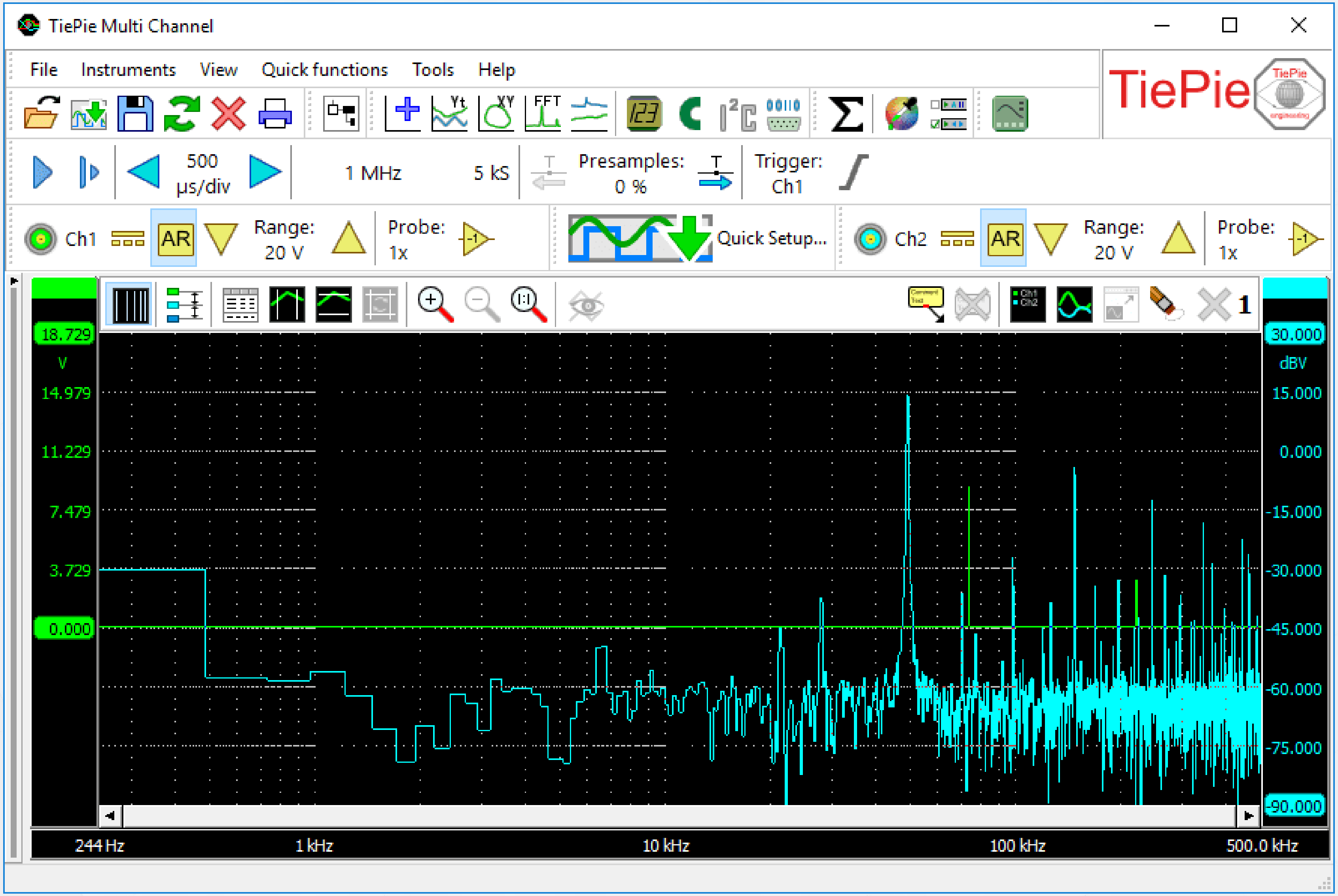
*Based on **TiePie Handyscopes***

HS6 DIFF: 250 MHz bandwidth, 1 GS/s, 14 bits, USB 3.0

HS5: 500 MHz, 14 bits, USB 2.0, 40 MHz AWG

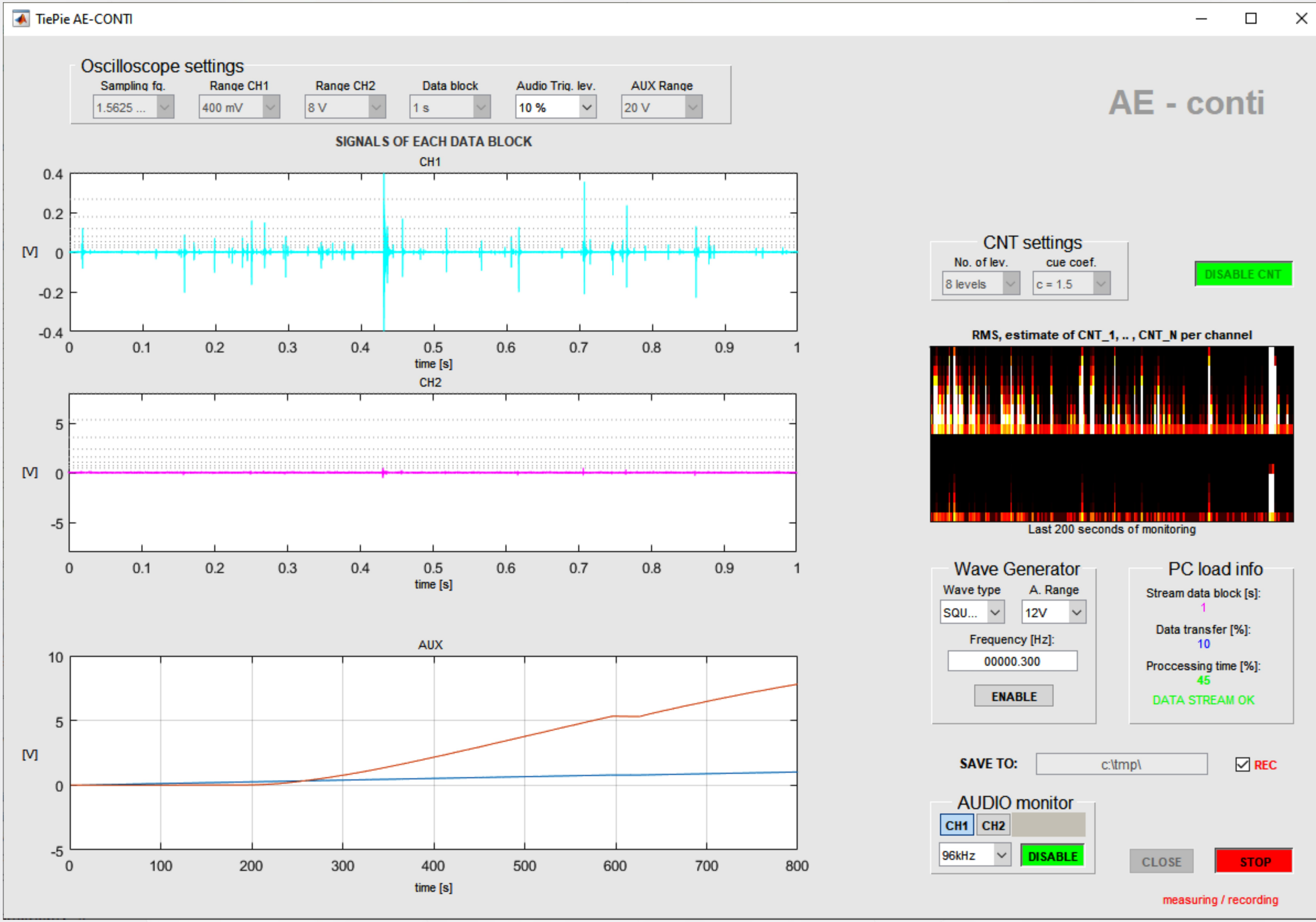
Multi unit synchr. feature:

NATIVE CONTROL SOFTWARE *(TiePie Multi Channel)*

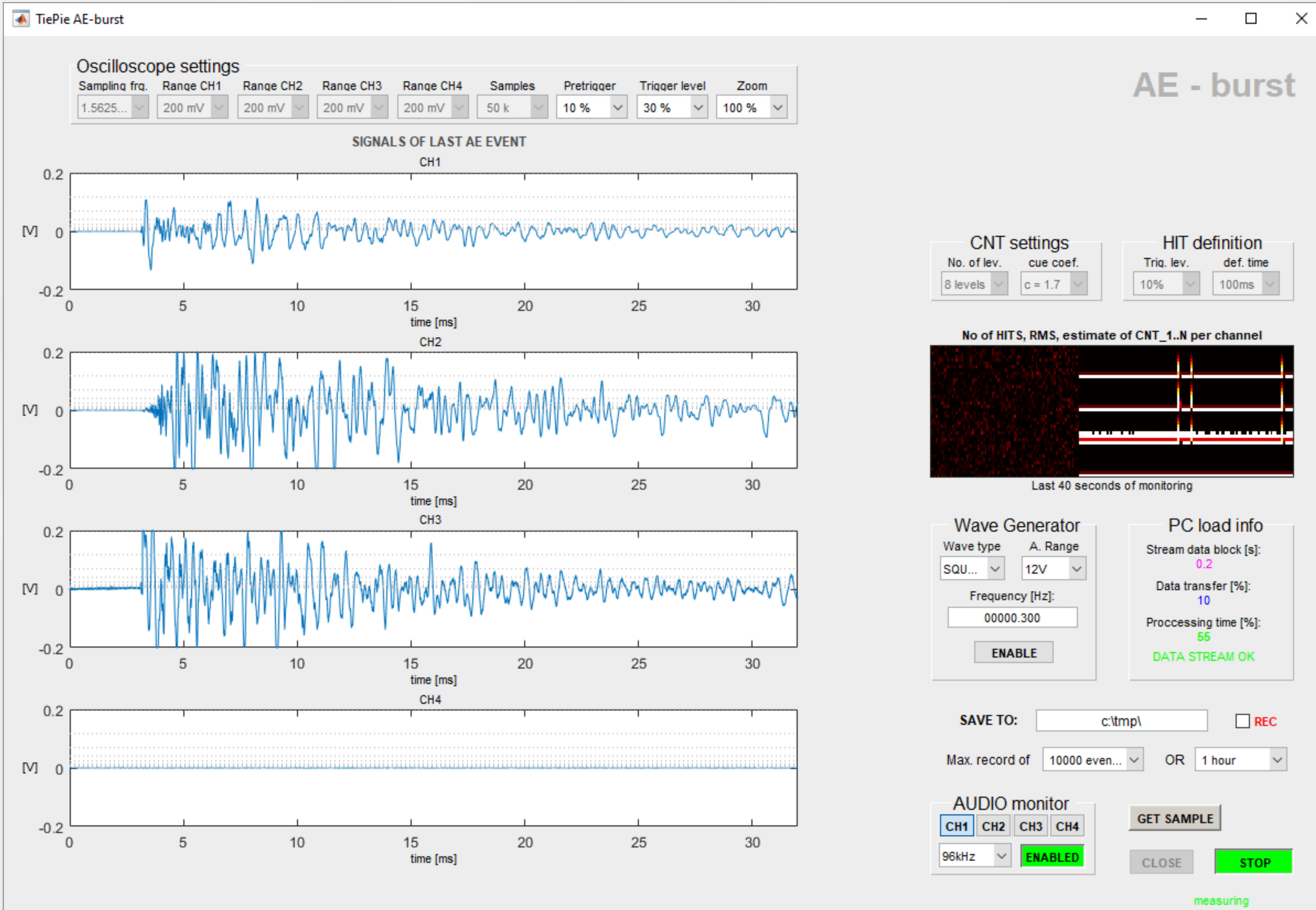


Ready to measure and analyze AE activity online?

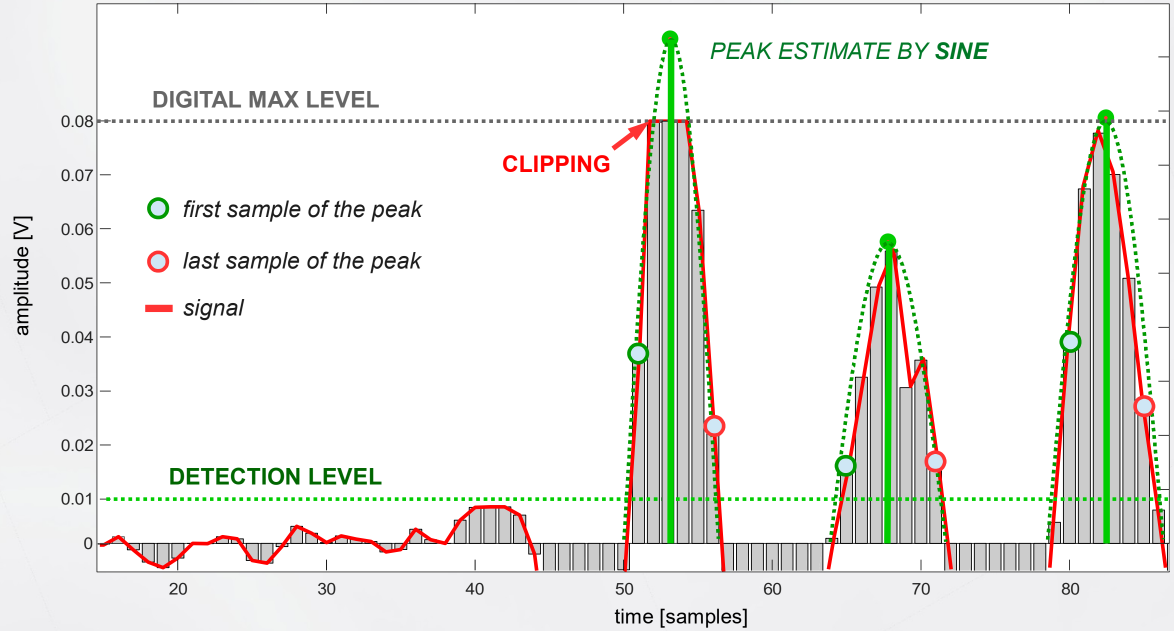
MATLAB AE MONITORING CODE *(with GUI for 2x HS5)*



MATLAB AE MONITORING CODE *(with GUI for HS6)*



PEAK AMPLITUDES ESTIMATE METHOD



ALGORITHM 1

1. compute **cumulative sum** *cs(i)* of the signal for all samples
2. find the first i_{first} and last i_{last} sample of each peak higher than the detection level
3. compute **integrals** of peaks using cumulative sum and estimate the **peak amplitude** ***A*** by:

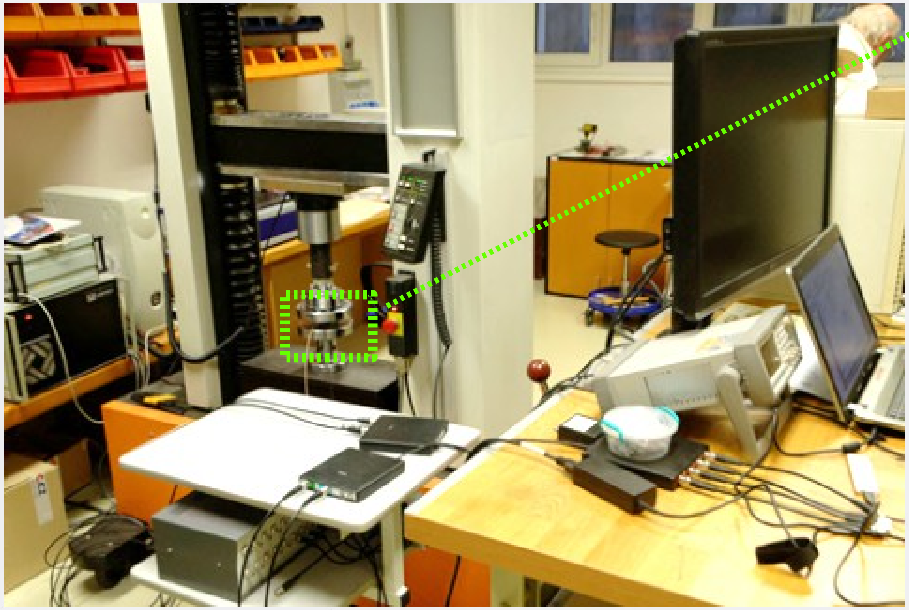
$$A = \Pi \cdot (cs(i_{last}) - cs(i_{first})) \ / \ 2 \cdot (i_{last} - i_{first})$$

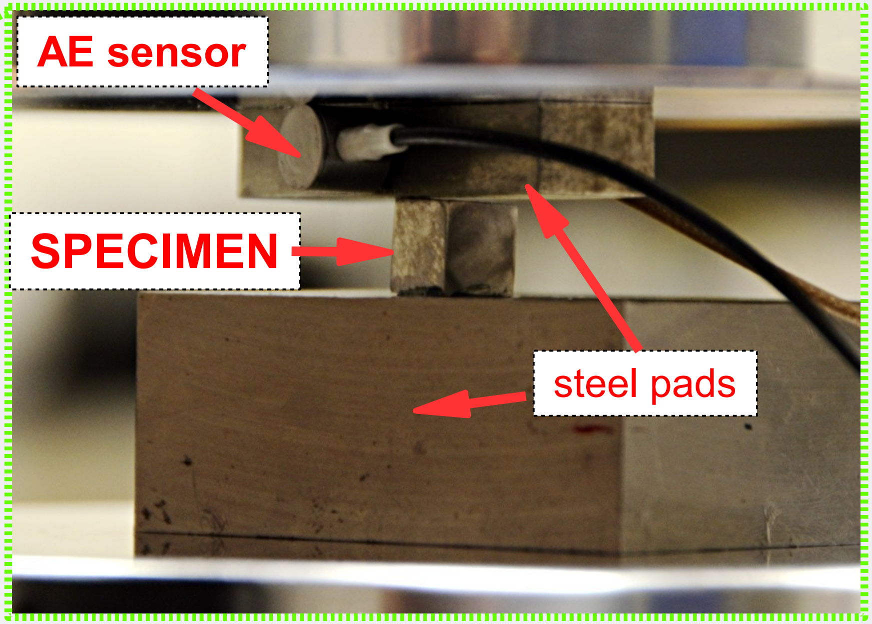
ALGORITHM 2

1. compute **cumulative sum** $cs^2(i)$ of the signal square for all samples
2. *similar to algorithm 1*
3. compute **integrals** of peaks using cumulative sum of **squared samples** and estimate the **peak amplitude** ***A*** by:

$$A = \sqrt{2 \cdot (cs^2(i_{last}) - cs^2(i_{first})) \ / \ (i_{last} - i_{first})}, \qquad \text{while true} \ \ RMS(s(1-N)) = \sqrt{cs^2(N)/N}$$

EXPERIMENT – static loading of *Ti-Mo-Si* alloys





TESTED SPECIMEN:

- **Ti-Mo-Si alloys** having specific strength and corrosion resistance and best biocompatibility among metallic materials for **medical prostheses**

(acknowledgements to Adriana Savin - National Institute of R&D for Technical Physics, NDT Department, Iasi, Romania)

MAIN GOAL OF EXPERIMENTS WAS TO TEST:

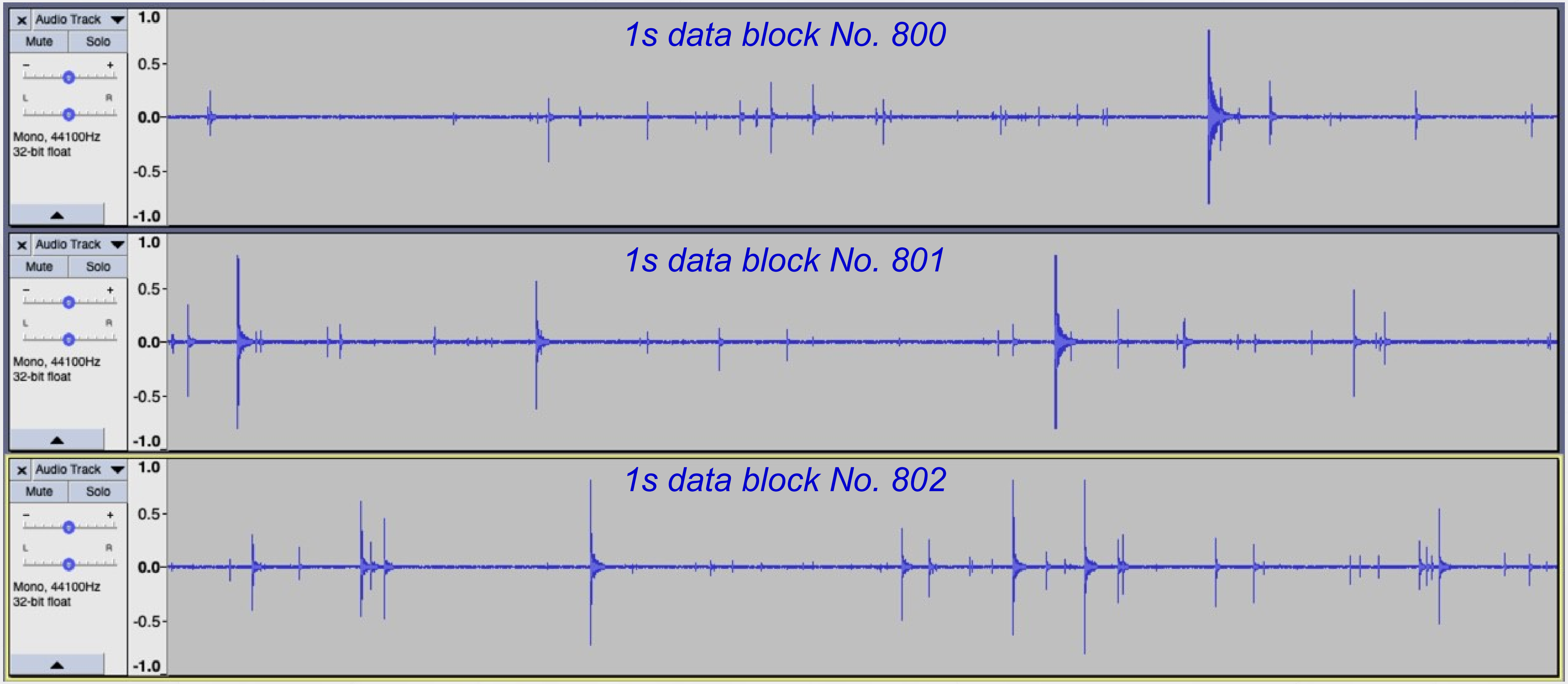
- the mechanical **properties and behavior** of the Ti-Mo-Si alloys *(improving the bio-functional characteristics of such medical materials)*
- the influence of **Mo** *(15-20%)* and **Si** *(0.5-1%)* **concentration** in alloys
- the probability of appearance and propagation of **cracks**

MONITORING METHOD:

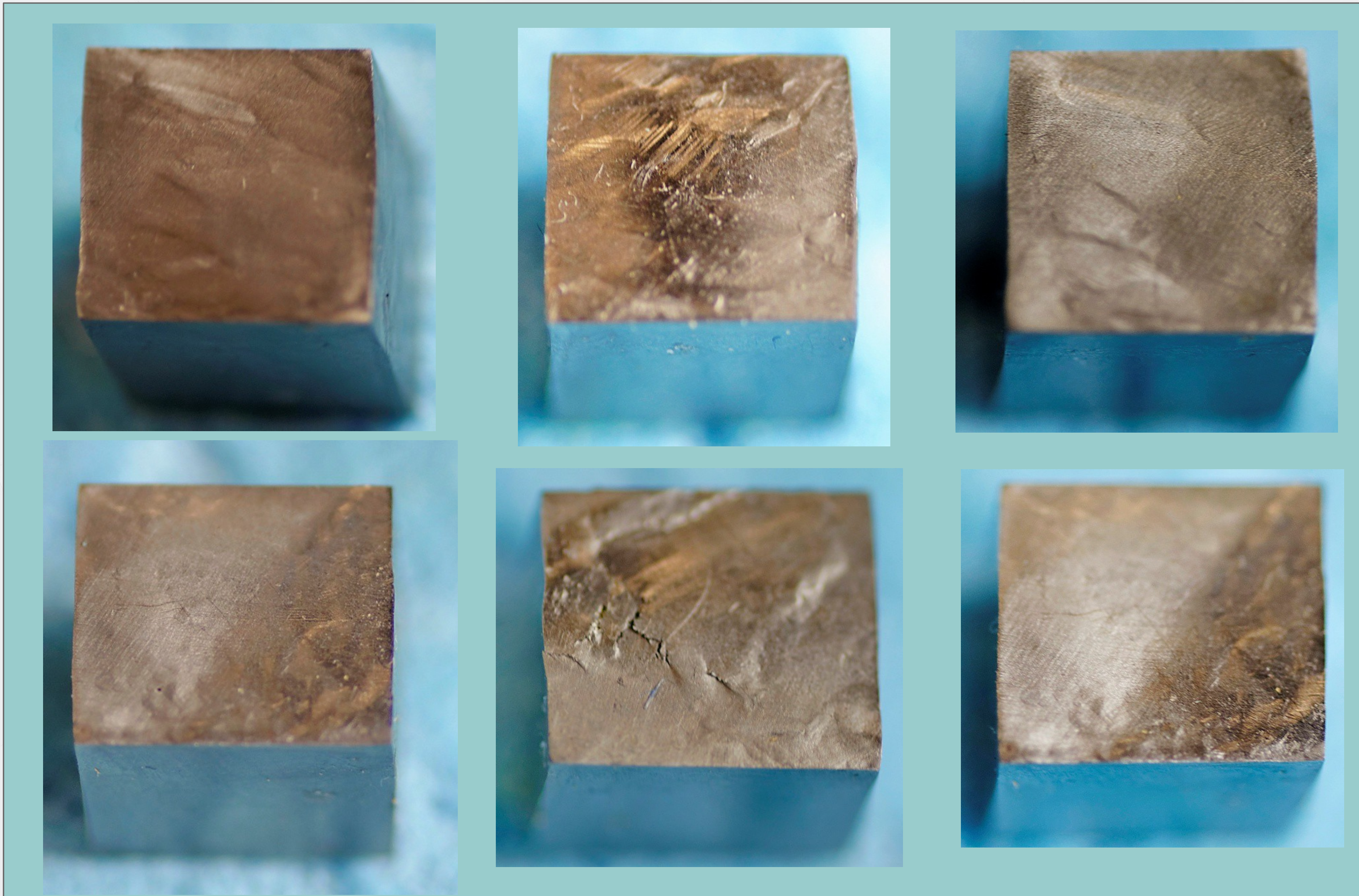
- acoustic emission as highly sensitive for detecting the initiation and propagation of micro-cracks *(piezo transducer, 20dB preamplifier, data streaming: 1MHz sampling, 12-bits amplitude resolution)*

AUDIO MONITORING OF CAPTURED SIGNALS

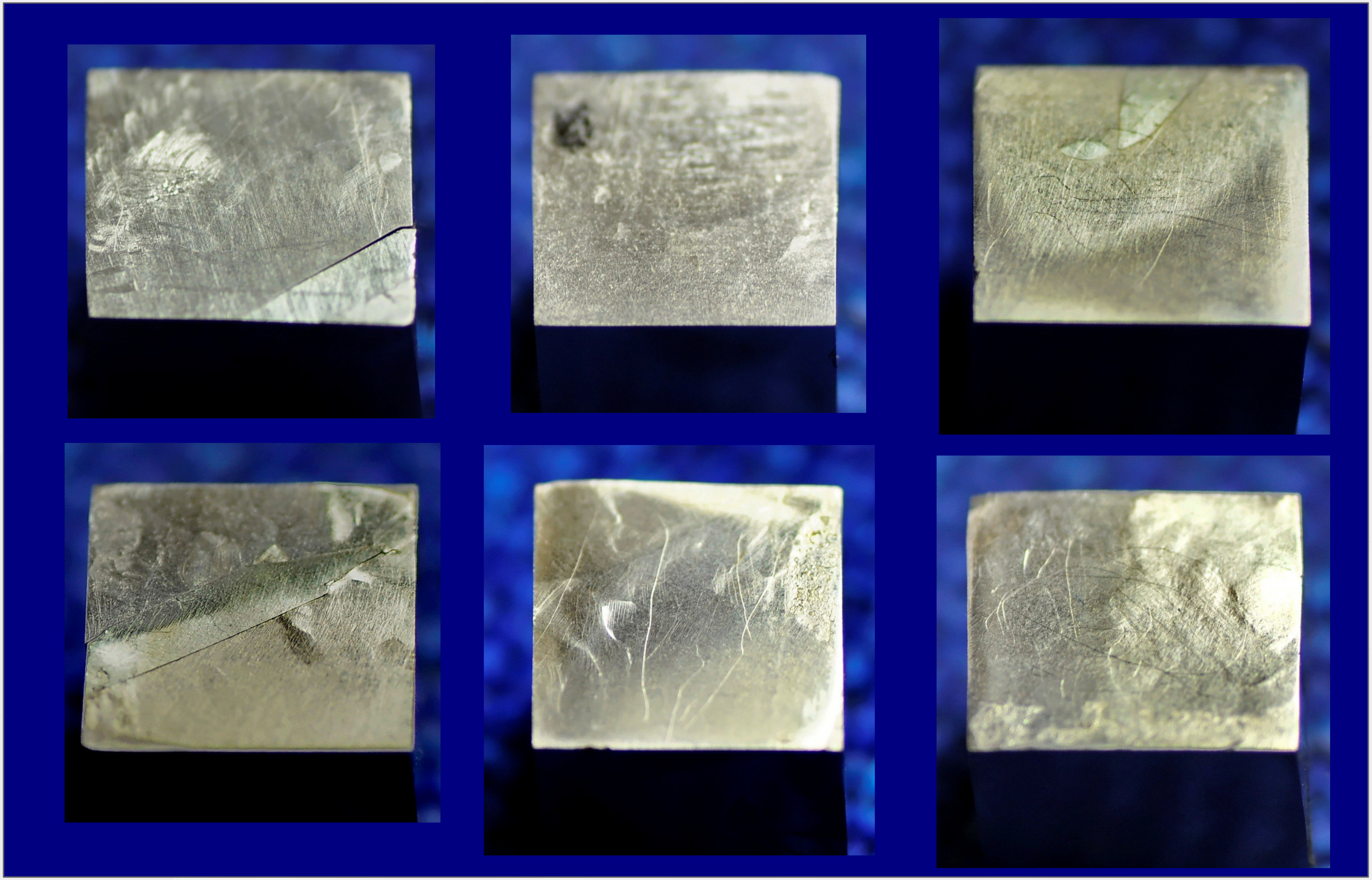
(speed ratio: 1 / 22.7 x)



SPECIMEN AFTER TESTING *(Ti - 15%Mo)*

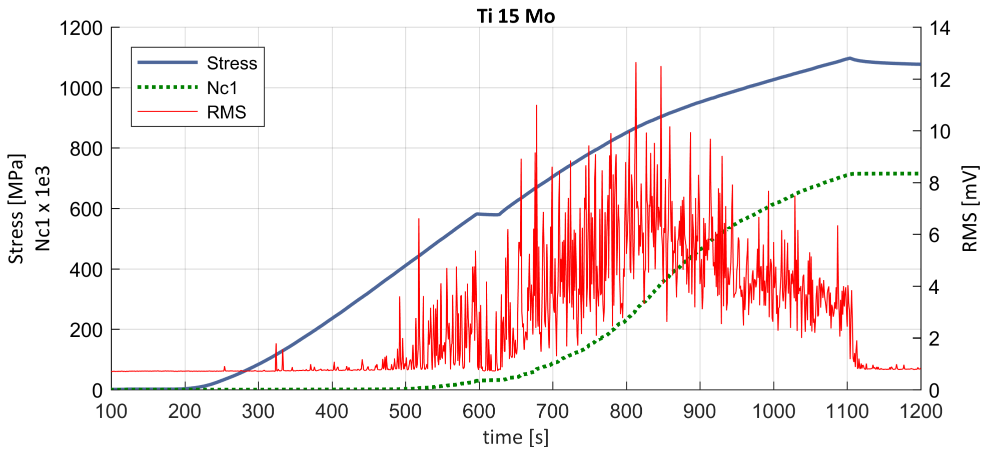


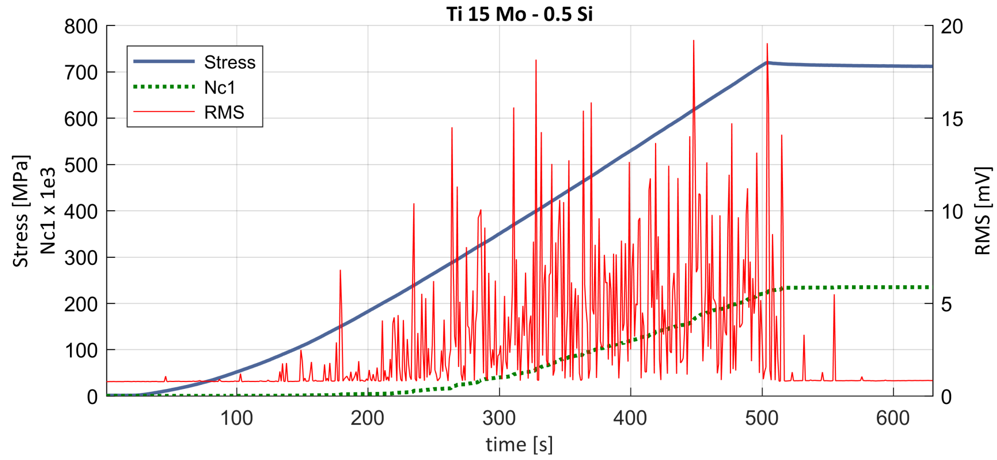
SPECIMEN AFTER TESTING *(Ti - 15%Mo - 0.5%Si)*

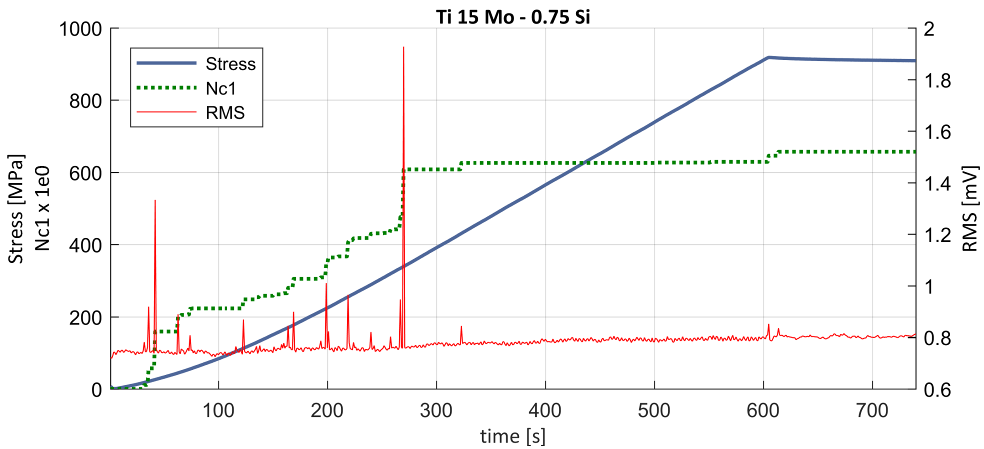


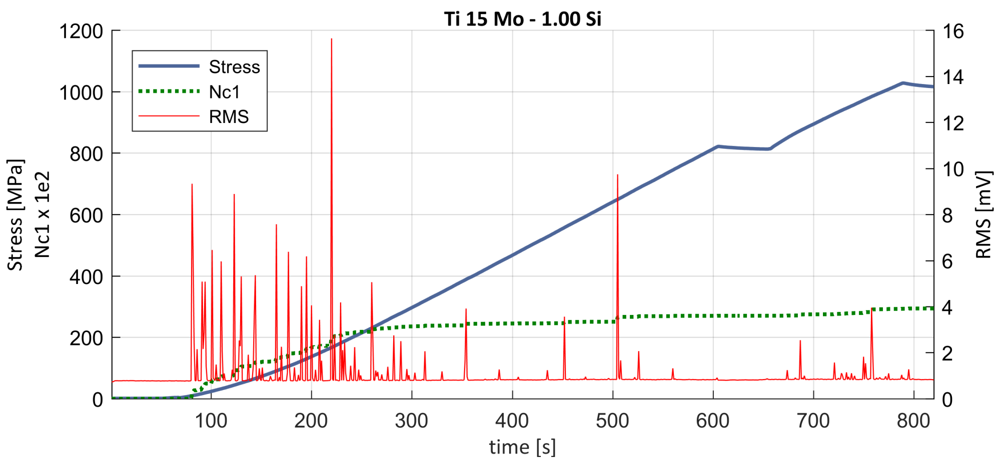
VARIABILITY OF AE ACTIVITY

(RMS, Number of counts and stress in time)

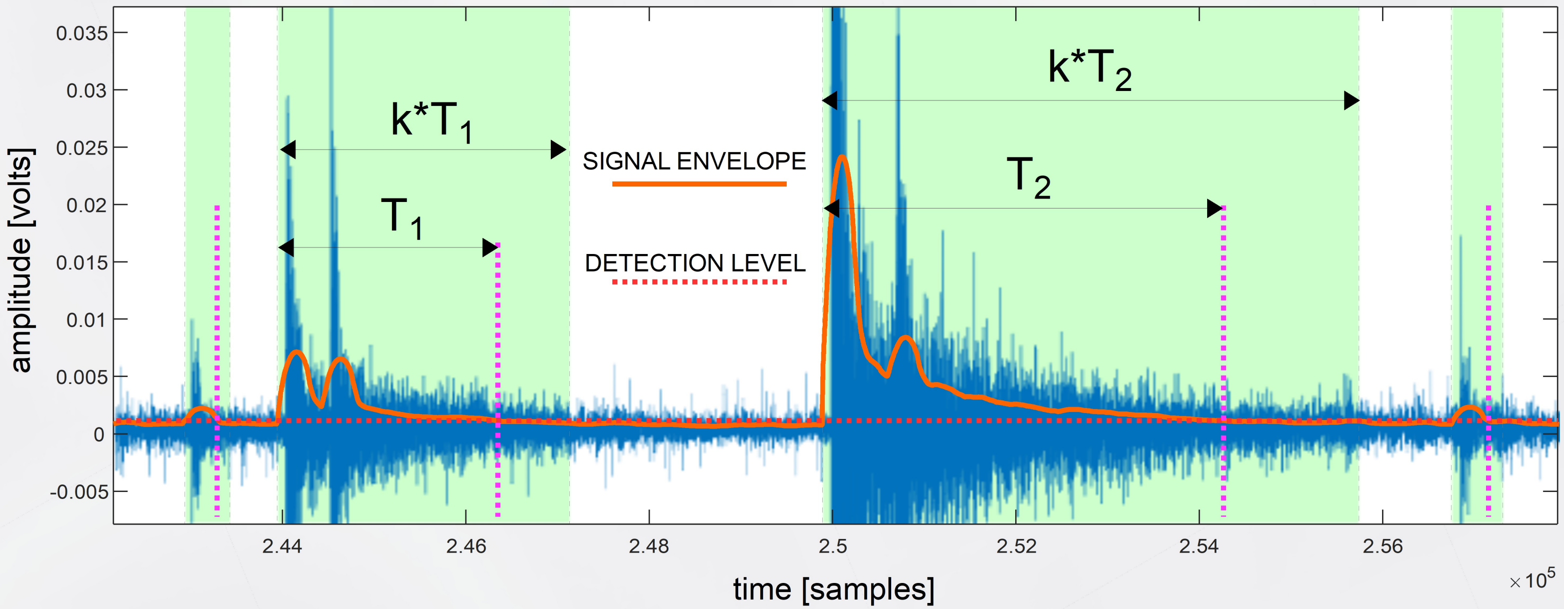








OFF-LINE AE *HIT DETECTION* AND *HFD-SPECTROGRAM* COMPUTATION



EXTRACTION OF AE HITS:

- calculation of the **signal envelope** *(convolution with the Hamming window of appropriately chosen length)*
- **AE hit** duration time corresponds to the multiple *(k=1.3)* of time period *T*, in which the signal envelope is above the detection level

"CORRELATION" METHOD OF SPECTRAL ANALYSIS

- classical FFT is not suitable *(variable signal length, needed to solve problems with common frequency resolution)*
- analogically to FT, it is possible to compute the measure p_{HFD} detecting frequency f_{rel} in signal s:

$$p_{HFD}(f_{rel}) = \left| \sum_{n=0}^{N-1} s(n) e^{i \Pi n f_{rel}} \right|^2 \quad , where \;\; f_{rel} \in (0,1) \; is\, relative\; frequency$$

HFD-SPECTROGRAM

- values p_{HFD} for extracted hits detected within ***each second*** of experiment were summed into corresponding column of ***HFD PSD*** *(frequency resolution 1kHz, while N_q=500kHz)*

PRINCIPLE COMPONENT AND FACTOR ANALYSIS

Factor analysis

A method for finding linear relations among parameters and computing reduced number of new, hypothetical variables *(factors)* explaining variance of parameters.

FA is based on Principal Component Analysis *(PCA)*, which has three effects:

- *orthogonalizing transformed input-vector components as they become uncorrelated*
- *organizing orthogonalized components (component having the largest variance is the first)*
- *eliminating components that contribute only little to the data set variance*

FA represents linear data transform (orthogonal rotation followed by scaling), following from the solution of equations:

$$Z = A \cdot P$$

Z - *original data*, **P** - *new hypothetical variables (factors)*

A - *factor scheme (represents the regression coefficients of factors to original variables)*

Factor scores estimate computing *(new uncorrelated signal features values):*

$$P = A' \cdot R^{-1} \cdot Z'$$

R - *correlation matrix of standardized data Z*

DEMONSTRATION OF FACTOR ANALYSIS

ROTATED FACTOR SCHEME (absolute values)

parameters \ factors	1	2	3	4	5	6
1	0.71	0.40	0.11	0.11	0.18	0.49
2	0.78	0.35	0.11	0.14	0.00	0.43
3	0.15	0.10	0.97	0.03	0.02	0.09
4	0.07	0.13	0.95	0.01	0.02	0.15
5	0.91	0.07	0.23	0.25	0.00	0.18
6	0.06	0.09	0.96	0.17	0.03	0.12
7	0.93	0.04	0.14	0.00	0.17	0.12
8	0.90	0.04	0.04	0.36	0.04	0.00
9	0.97	0.02	0.16	0.08	0.12	0.10
10	0.94	0.03	0.00	0.28	0.03	0.02
11	0.13	0.92	0.11	0.21	0.17	0.13
12	0.07	0.97	0.08	0.05	0.03	0.02
13	0.07	0.97	0.08	0.18	0.06	0.04
14	0.14	0.85	0.20	0.44	0.11	0.00
15	0.26	0.81	0.12	0.40	0.14	0.00
16	0.37	0.25	0.06	0.59	0.65	0.07
17	0.15	0.24	0.42	0.82	0.03	0.05
18	0.36	0.15	0.15	0.87	0.20	0.04
19	0.22	0.22	0.07	0.92	0.05	0.05

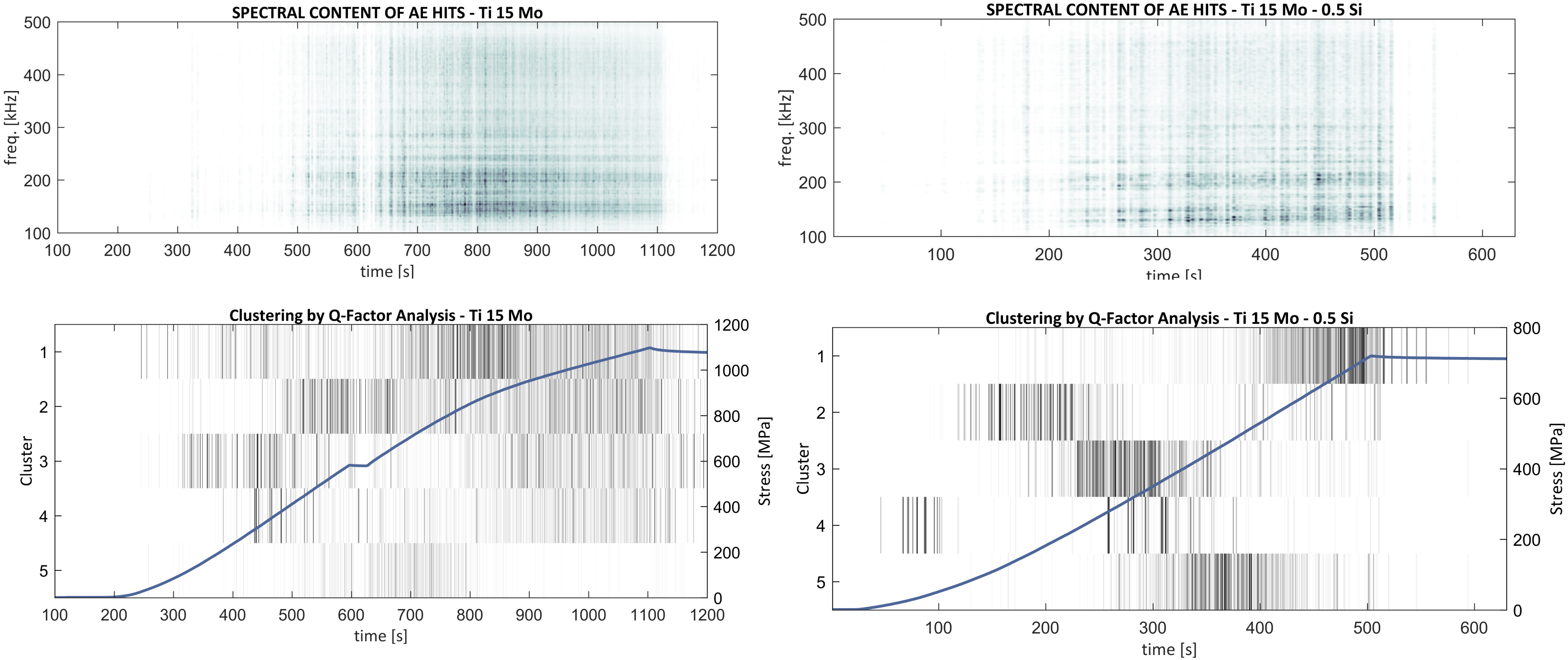
Results:

No. of extracted factors:
6

Interpreted data variance:
96%

SPECTRAL ANALYSIS OF AE HITS

(HFD PSD estimate and it's Q-factor analysis)



"Q method" of Factor Analysis computes correlations between measurements across a set of variables. QFA finds a few "typical shapes" of variable profiles, so called **"factors"**, which are claimed to be typical representatives of the measuremet diversity.

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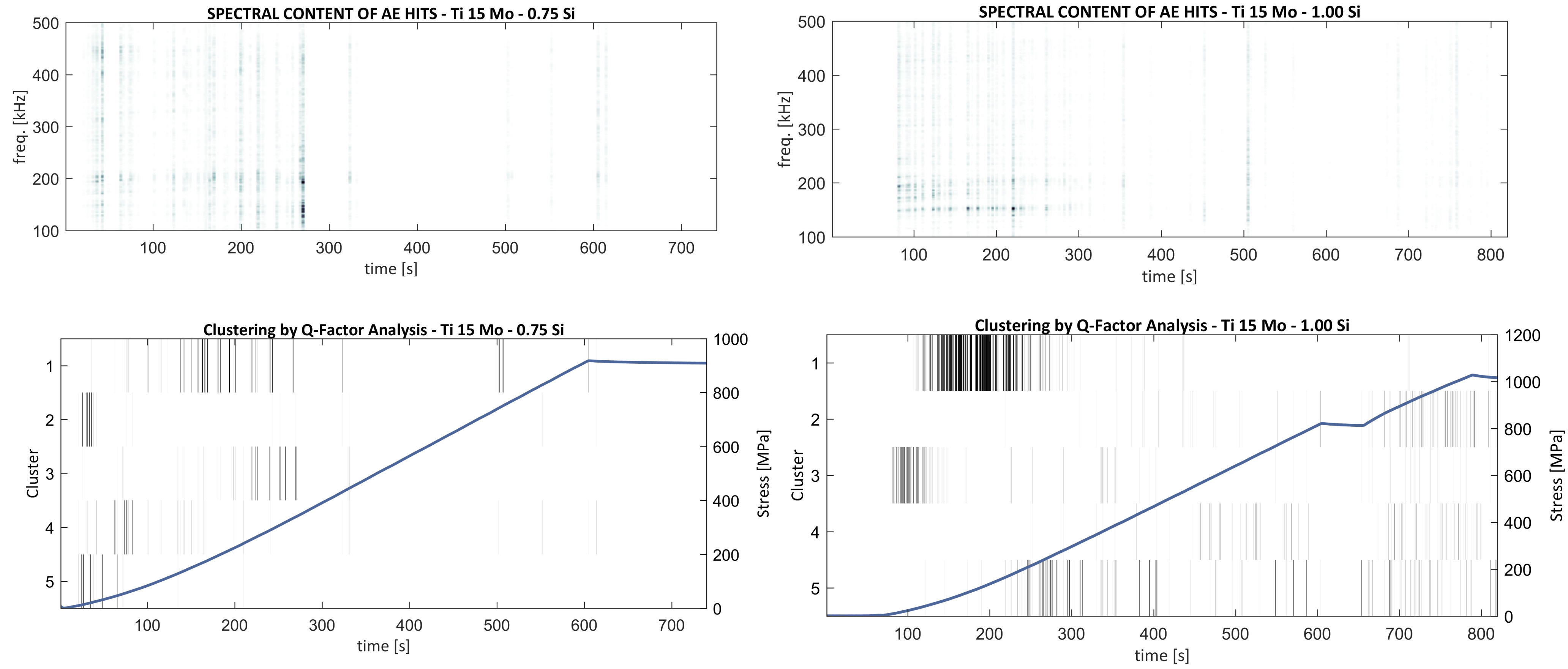

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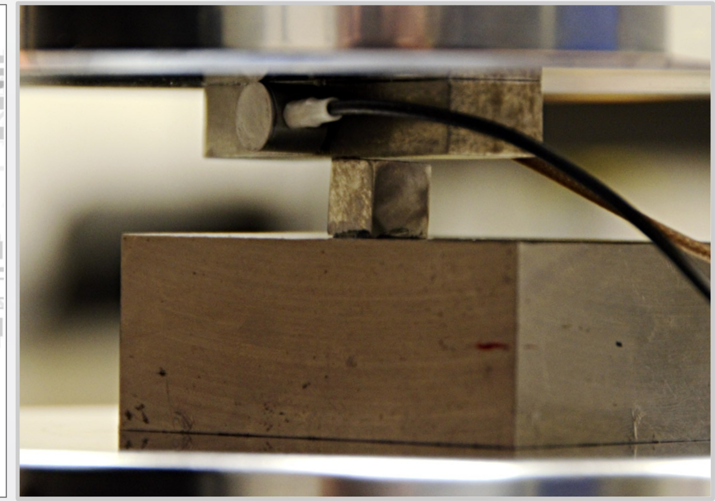

CONCLUSION

- Small AE systems based on streaming oscilloscopes prooved well for continuous monitoring of emission activity during static loading of Ti-Mo-Si alloys
- This approach enabled to verify the influence of molybdenum and silicone concentrations in alloys used for orthopaedic prosthesis.

THANK YOU FOR YOUR ATTENTION...