CEBE IAB meeting, May 19, 2015

Signal Processing in Impedance Spectroscopy

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Centre for Research Excellence CEBE

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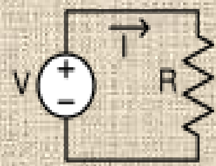
Electrical Impedance

Henry Cavendish
born in Nice (Nizza)
1731-1810



Ohm*'s *law

1826 $I = \frac{V}{R}$

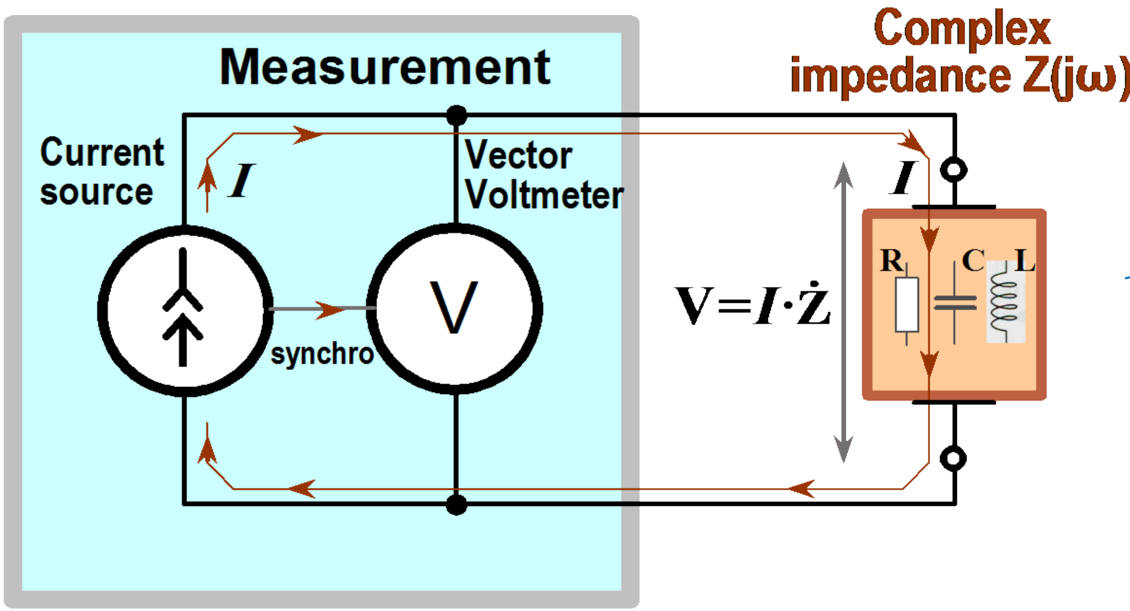
Oliver Heaviside
introduced the terms:
-**impedance** in July **1886**
-**admittance** in Dec **1887**

Arthur Edwin Kennelly
innovator and engineer
A paper **"Impedance"** in **1893**:
complex numbers
to Ohm's law for AC

Electrical impedance (or simply impedance) is a measure of opposition to ***sinusoidal*** electric current

The concept of electrical impedance generalizes Ohm's law to AC circuit analysis. Unlike electrical resistance, the impedance of an electric circuit can be a complex number: $Z = V/I$, where $Z = R + jX$, and R is a real part and X is an imaginary part.

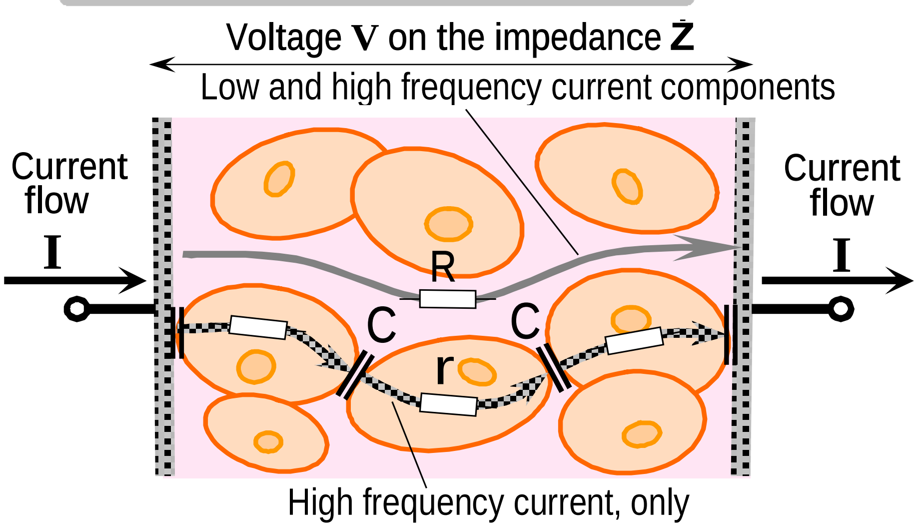
Complex Impedance characterises structures and electric properties of materials, substances, devices, constructions

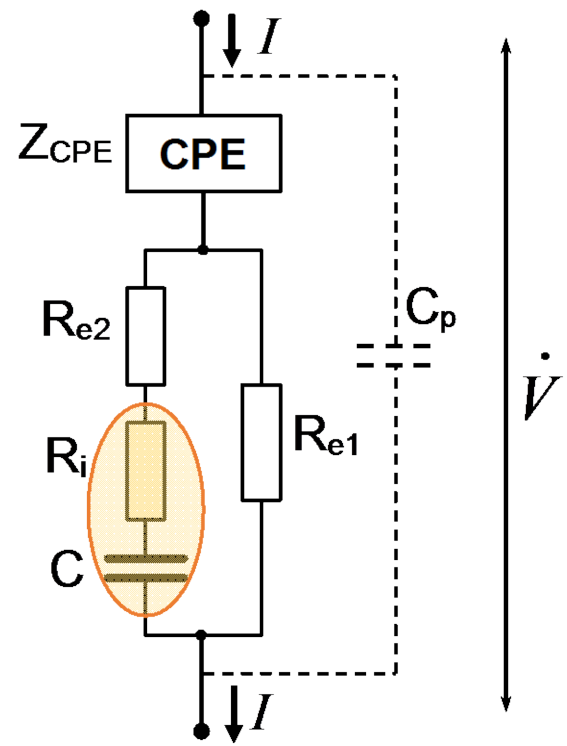


$$Z(j\omega) = R + X(j\omega)$$

$$X_C(j\omega) = 1/j\omega C = -j(1/\omega C)$$

$$X_L(j\omega) = +j\omega L, \quad \omega = 2\pi f$$



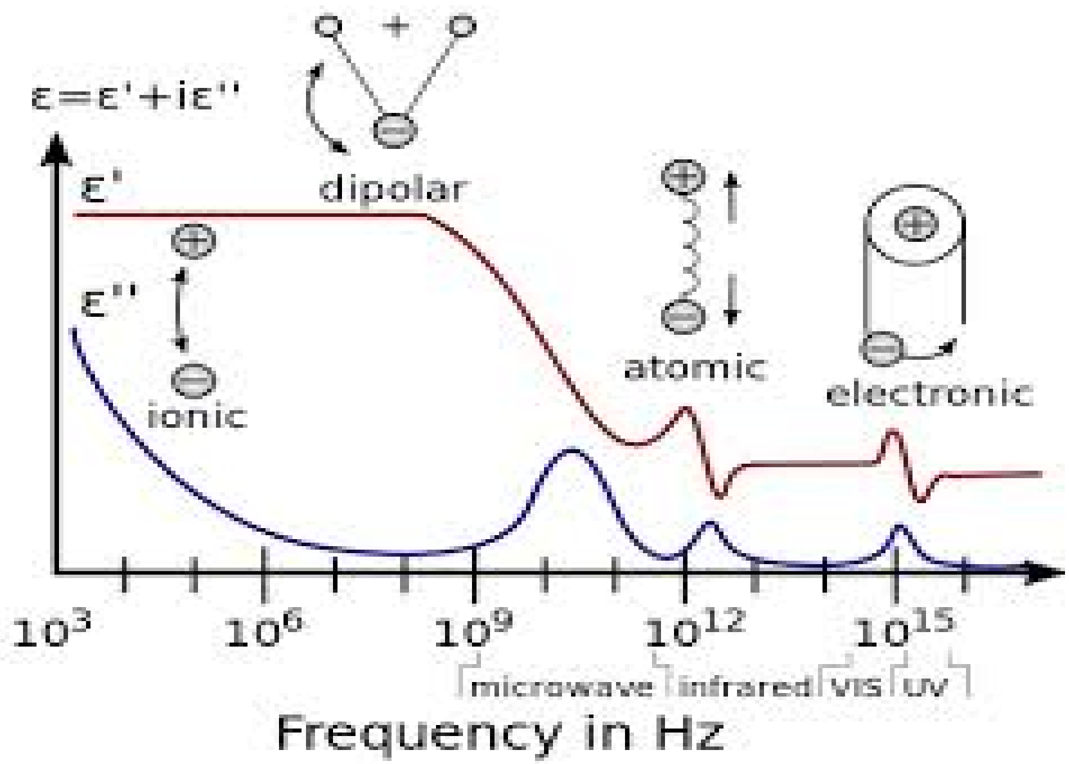


Complex Impedance depends also on dielectric properties of material: complex permittivity versus frequency

$$\varepsilon(j\omega)=\varepsilon'(\omega)+j\varepsilon''(\omega),\quad \omega=2\pi f$$

Imaginary capacitive impedance $X_c = 1/j\omega C$,

the capacitance $C = \varepsilon A/d$ depends on $\varepsilon(j\omega)$



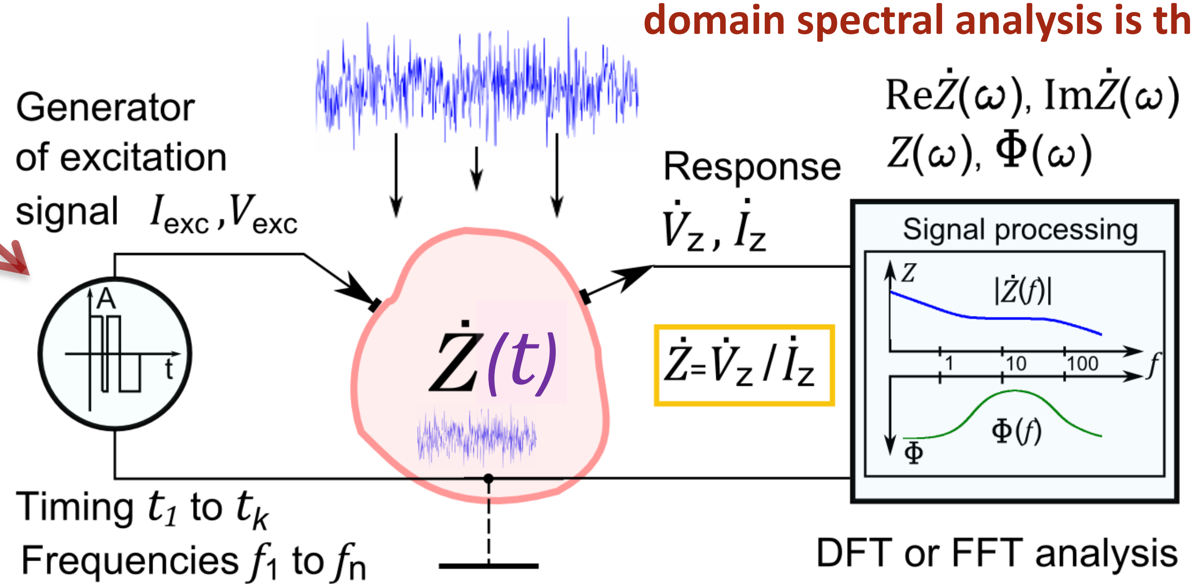
Introduction to Impedance Spectroscopy

In most cases the impedance spectrum of biological objects must be measured fast.
Examples: flowing cells in microfluidic devices, cardiovascular system, beating heart, breathing lungs, pulsating blood, …

The best accuracy of time-frequency domain spectral analysis is the aim

Excitation amplitude is severly limited!

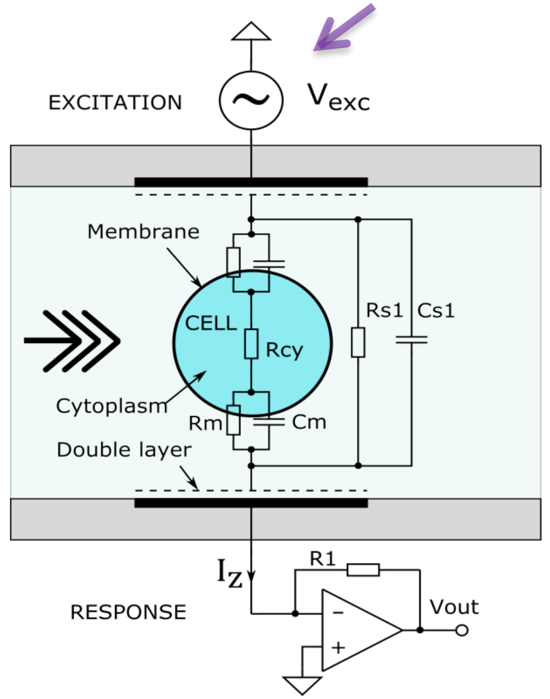
- safety regulations
- nonlinearities of object
- Impact on the object parameters
- energy consumption



<u>The question to be answered</u>: how to perform the fast impedance spectroscopy within the needed frequency range (from f_1 to f_2) during a required short time interval (from t_1 to t_2) with minimum dynamic uncertainty and the lowest noise level.

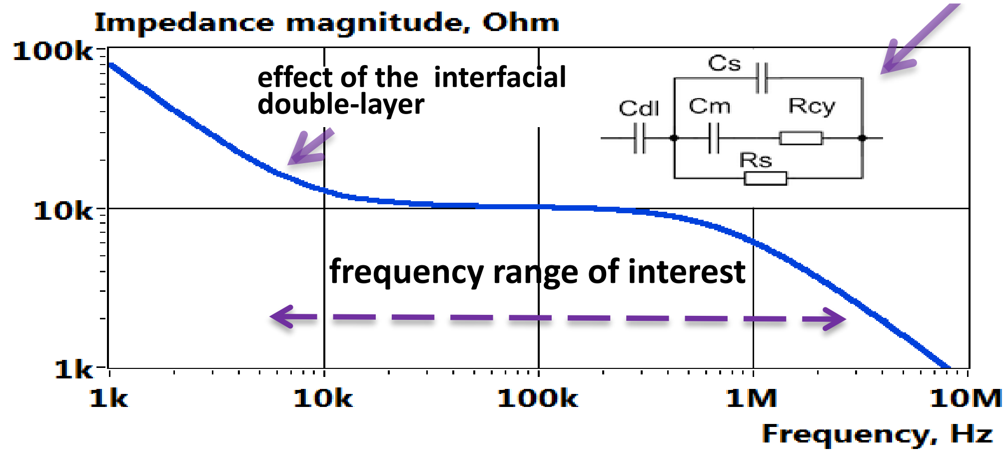
Spectrally rich excitation is required (microfluidic cytometry as an example)

≤ ∓ 50 mV (to avoid nonlinearities)

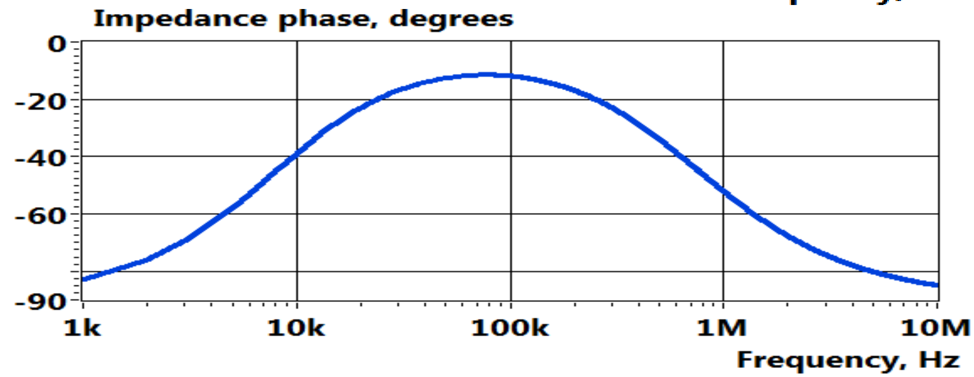


Simplified electrical model

Equivalent circuit



Cdl = 2 nF
Cm = 1 pF
Cs = 20 pF
Rs = 10k
Rcy = 100k

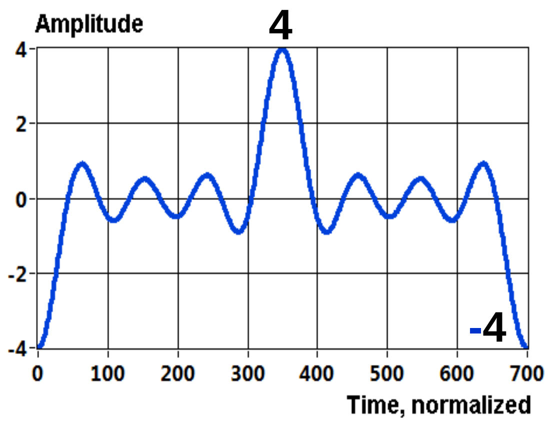


Since the shape of impedance spectrum is smooth, it is not reasonable to spread the excitation energy over all the frequency range but to concentrate it onto limited number of discrete frequencies (frequency bins). Spectrally sparce excitation is recommended in this case.

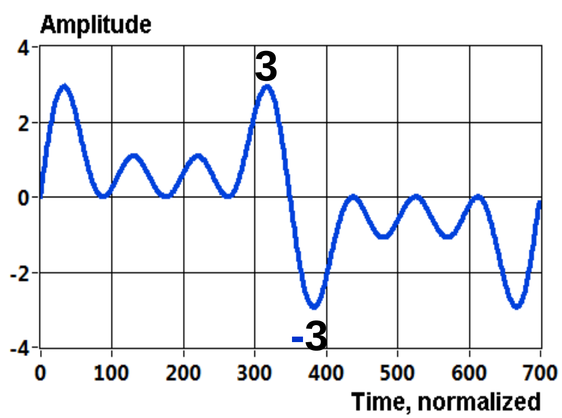
Spectrally rich but sparse excitation: a multisine signal

$$S(t)=\sum_{i=1}^{i=k} A_i \cdot \sin(2\pi f_i + \Phi_i)$$

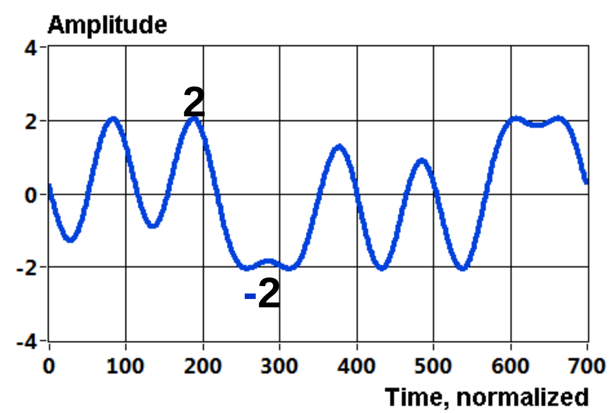
Sum of 4 sine wave components (k = 4) with frequencies 1f1, 3f1, 5f1, 7f1 and A_i = 1



Sum of 4 sine waves
Φi = 90° , CF = 2.83



Sum of 4 sine waves
Φi = 0°, CF = 2.08



Sum of 4 sine waves
Φi = optimized, CF = 1.45

Crest Factor (CF) – an important parameter for the excitation signal

$$CF = \frac{\underset{t\in[0,T]}{Max}|s(t)|}{\sqrt{\frac{1}{T}\int_0^T s^2(t)dt}}$$

Peak value of the excitation signal $s(t)$

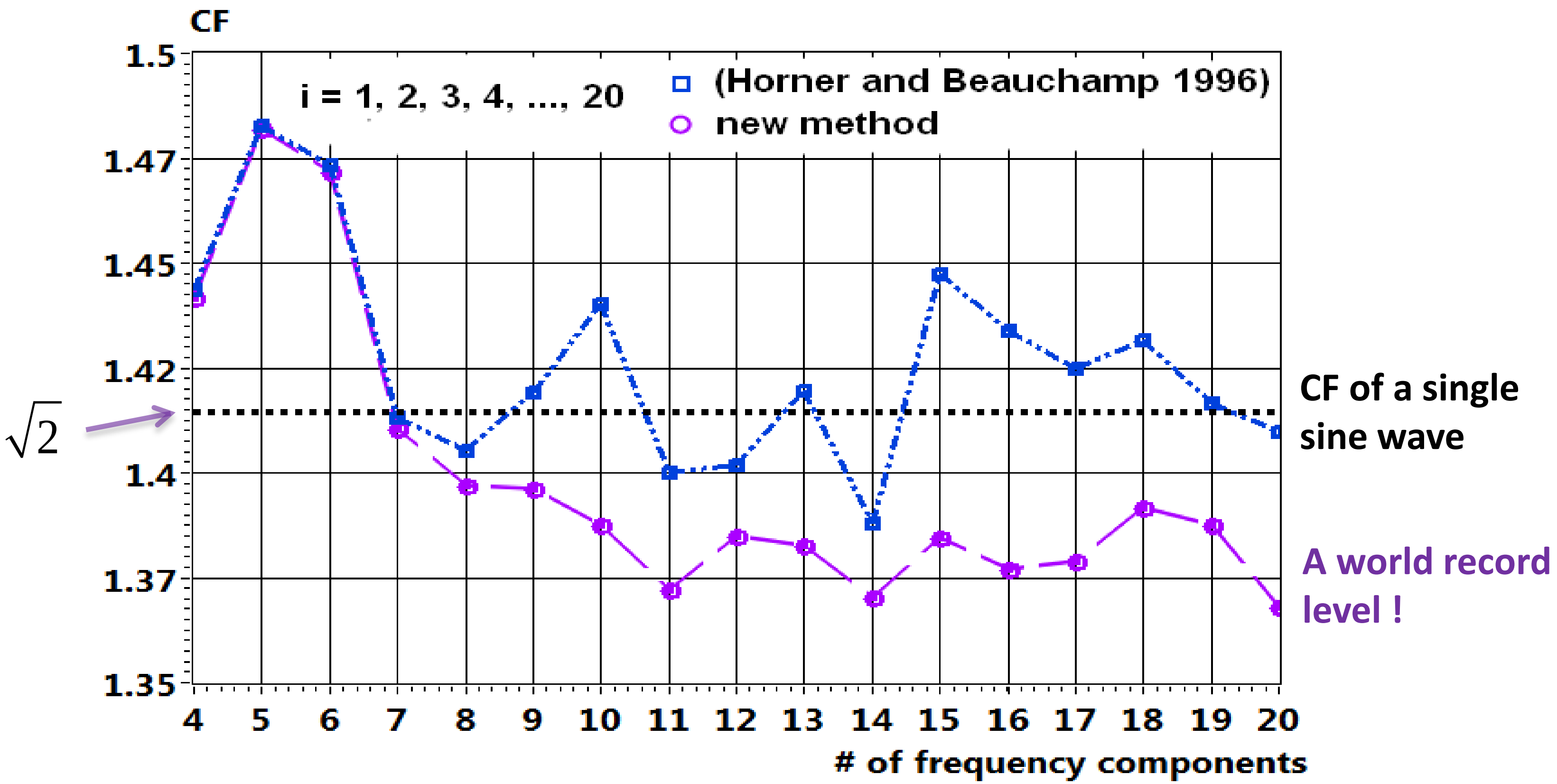
RMS value of the excitation signal $s(t)$

T denotes the observation time of the multicomponent signal $s(t)$

RMS value does not depend on initial phases Φ(*i*) of separate components. The CF minimization problem reduces to finding the best set of phases, which ensures the minimum peak value for the excitation.

Result – the best packaging of energy into a signal with limited amplitude!

CFs of the optimized multisines:
consecutive frequency distribution (4, 5, 6, ... , 20)



Recent results of the CF optimisation using the developed new method by J.Ojarand, M. Min and P. Annus, Physiol. Meas. vol. 35 pp. 1019–1033, 2014.

Enhanced optimisation: minimization of the crest factors of both - excitation (CF_E) and response (CF_R)

Crest factor CF_R of the response signal depends on the crest factor CF_E of the excitation signal, but not directly.

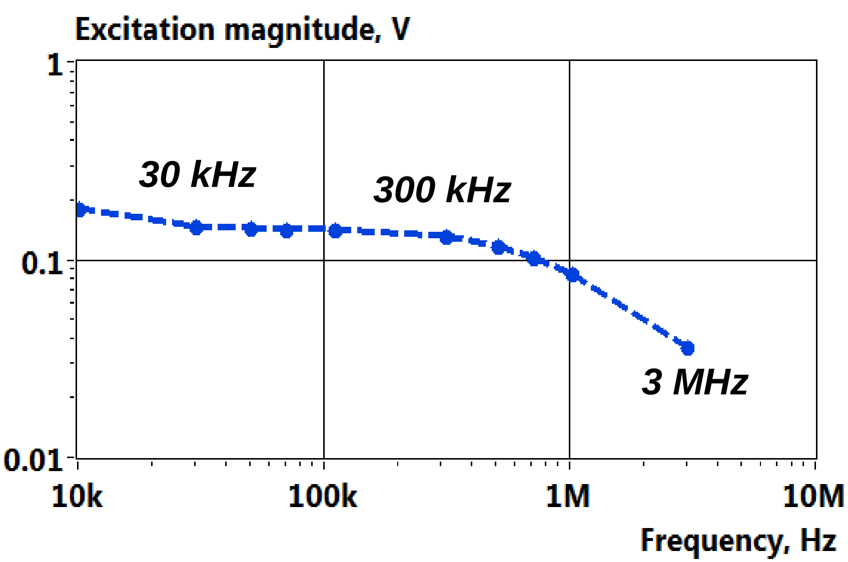
1. CF_E of the multisine excitation depends on initial phases of its components that are freely adjustable and can be optimized, therefore.
2. Phases of the response signal components will not remain the same as of the excitation has. They depend also on the phase shifts in object or the sample under test (SUT).

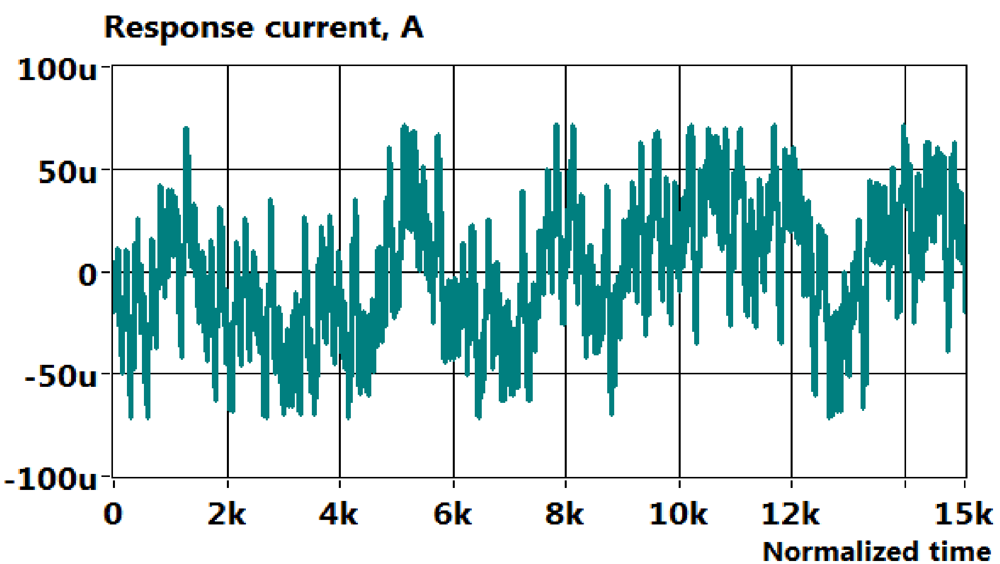
The idea for enhanced optimization of the excitation signal:

Parameters of the excitation signal components (initial phases $\Phi(i)_{opt}$ and amplitudes $A(i)_{opt}$) should be modified so that the product $CF_{ER} = CF_E \times CF_R$ of crest factors of the excitation signal (CF_E) and the response signal (CF_R) will be minimal.

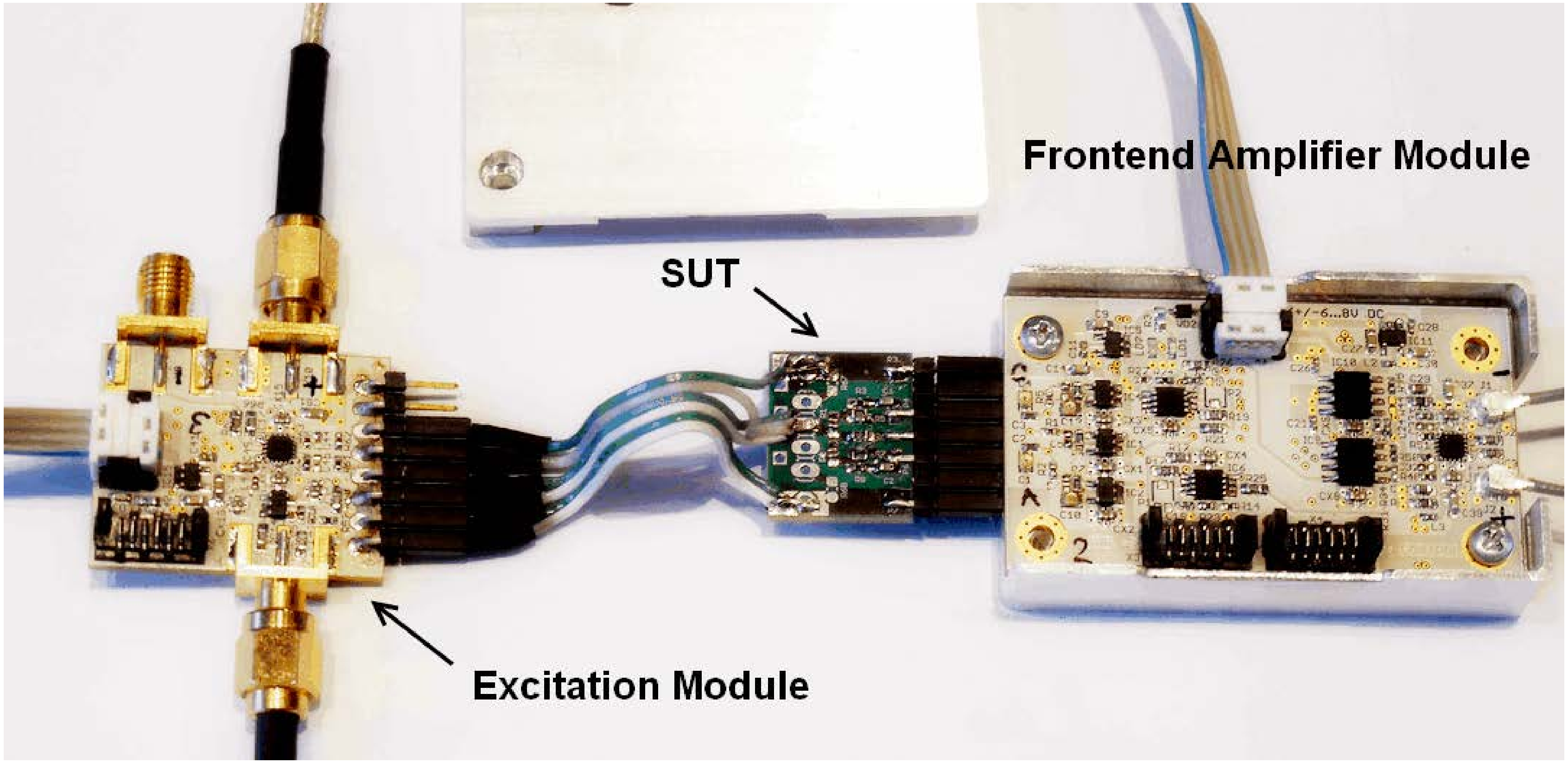
Enhanced optimization of the excitation signal: one experimental case

A multisine signal containing 10 frequency components was used as an excitation voltage. RMS magnitudes of all the spectral components of the response current were equalized to 10 μA using the magnitude $|\mathbb{Z}|(j\omega)$ of complex impedance $Z(j\omega)$. More than 30% higher signal-to-noise ratio has been achieved in comparison of the optimisation of excitation signal only.

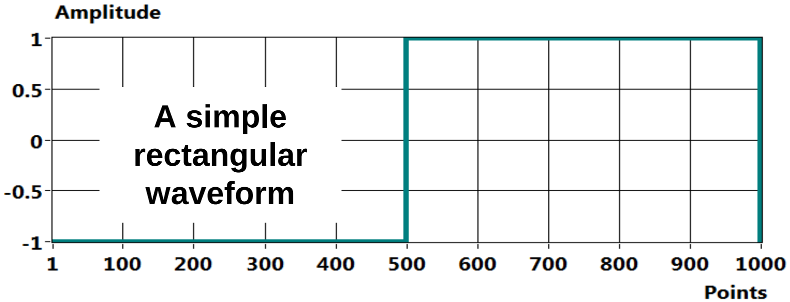


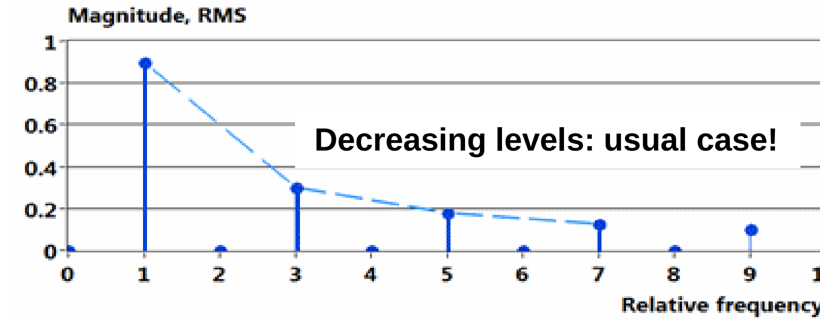


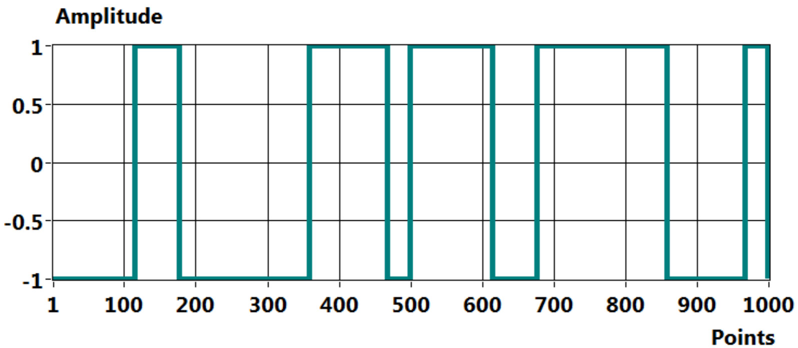
Electronics used in microfluidic experiments

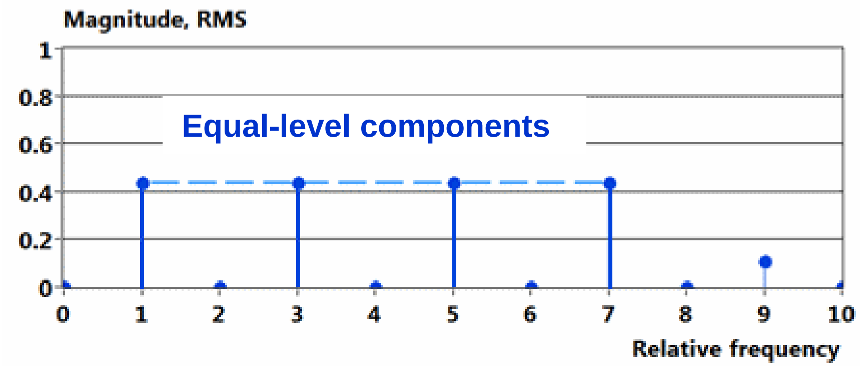


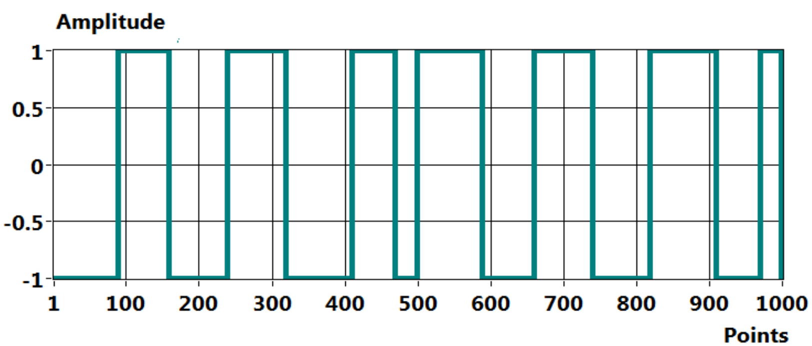
Making generation simpler: a multifrequency binary sequence as an excitation (4 frequences – *1, 3, 5, 7f*)

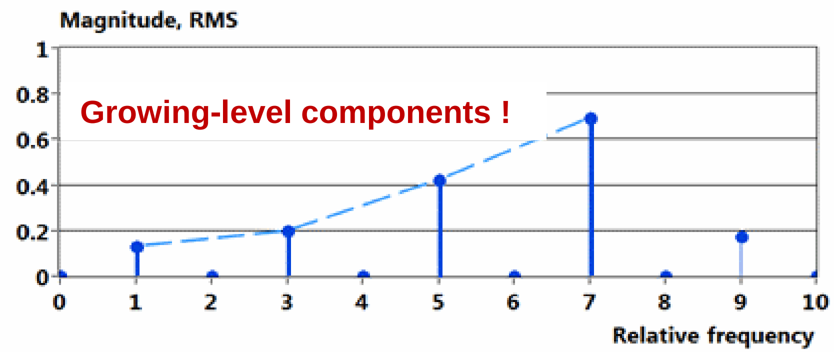












QUADRA™ TECHNOLOGY FOR IMPEDANCE SPECTROSCOPY

Basic solution – proof-of-concept prototype, hard & software.

CEBE partner: Th. J. Seebeck Department of Electronics.

Cooperation: ELIKO Competence Centre.

IP: Patent EE05668B1 (Estonia),
Patent Applications EP2565654A2 (EU),
and US2013/0054178 A1 (USA); Utility Model Application U201300075 (Estonia).

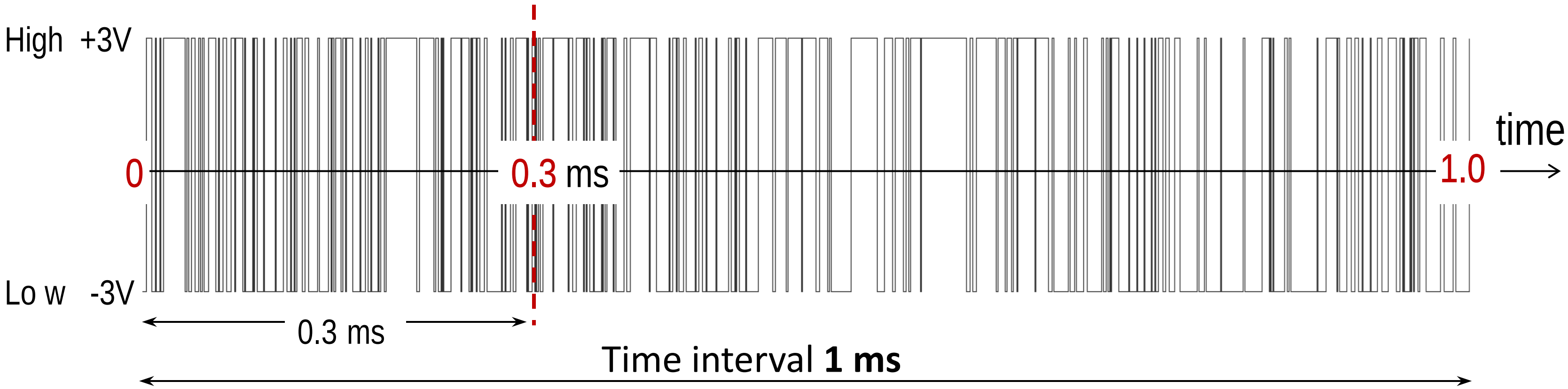
Operation principle: expandable multi-channel device generates a spectrally rich binary excitation containing 15 spectral lines to the system under study. The multi-frequency response signal is digitized and processed in parallel using time-frequency domain DFT.

Specifications:

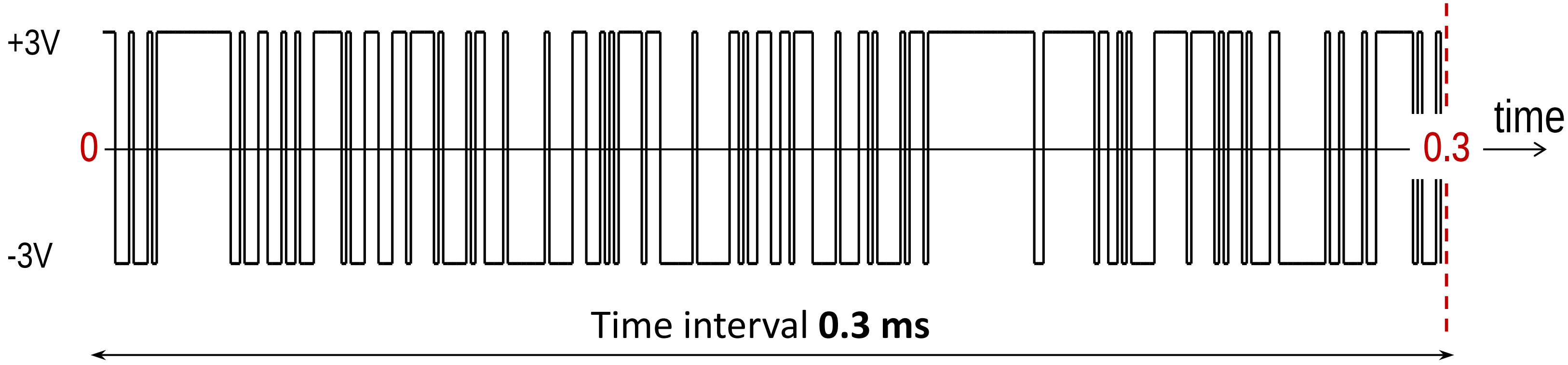
- Impedance measurement range: 10 Ω to 100 kΩ;
- Frequency range: selectable from 1 kHz to 350 kHz, resolution 1 kHz;
- Number of the frequency components: selectable from 4 to 15;
- Measurement time: selectable, min 1ms.

Practical case: 1ms cycle based binary excitation with the spectrum from 1kHz to 350 kHz, 15 spectral lines

(a) a full **1** ms cycle of binary excitation

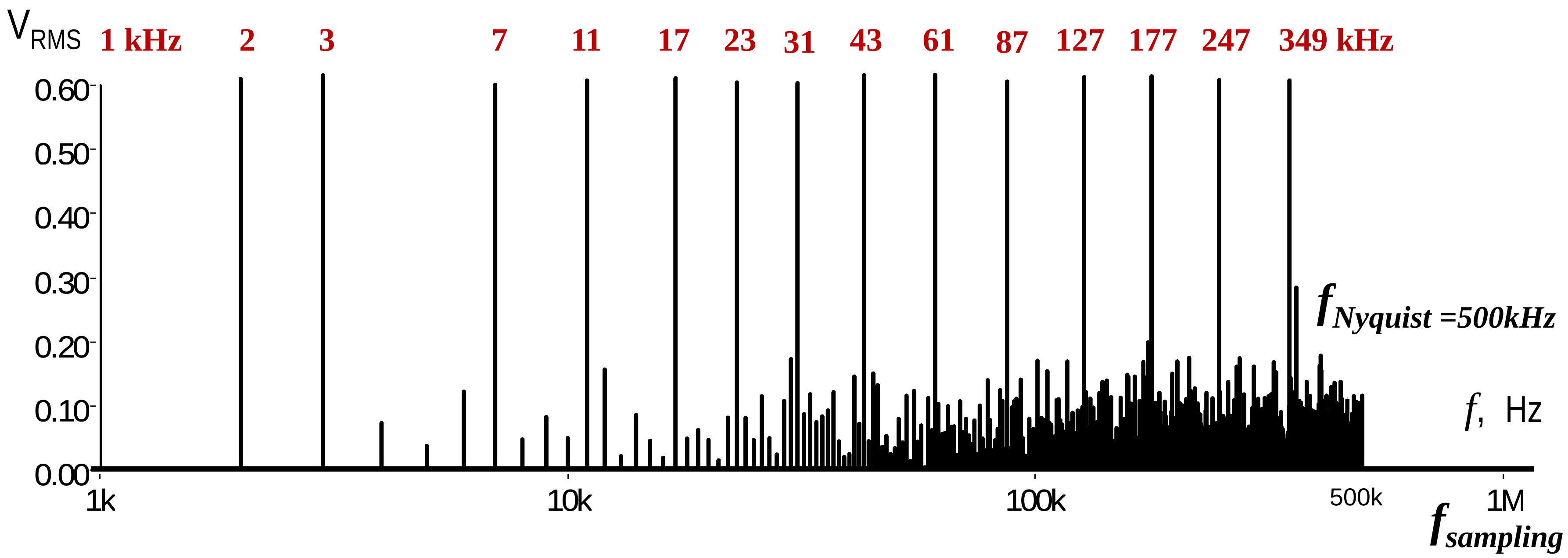


(b) initial **0.3** ms time interval zoomed out from the 1ms cycle.



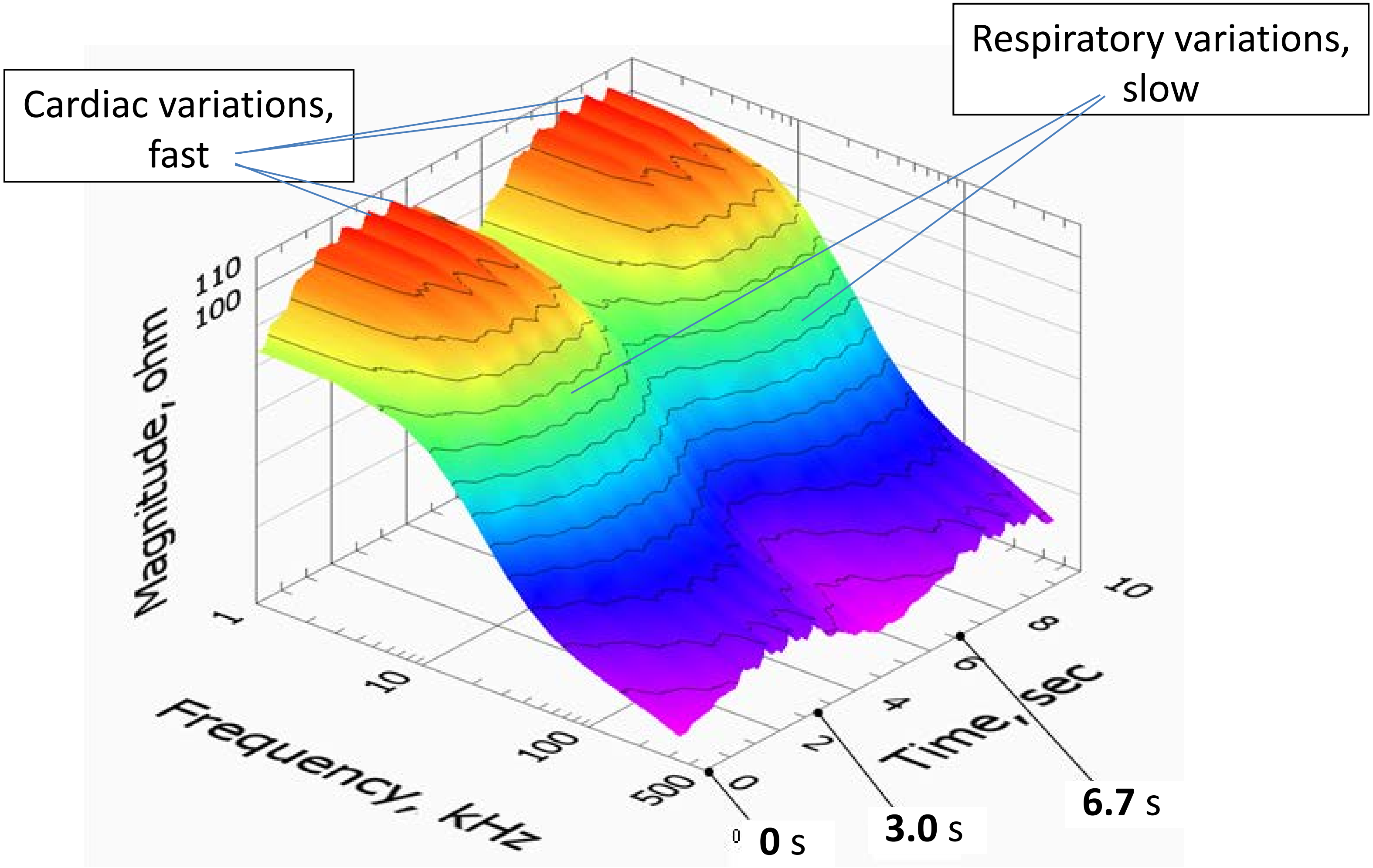
Spectrum of the used binary sequence

The spectrum contains 15 equal-amplitude frequency components
(a log frequency presentation)



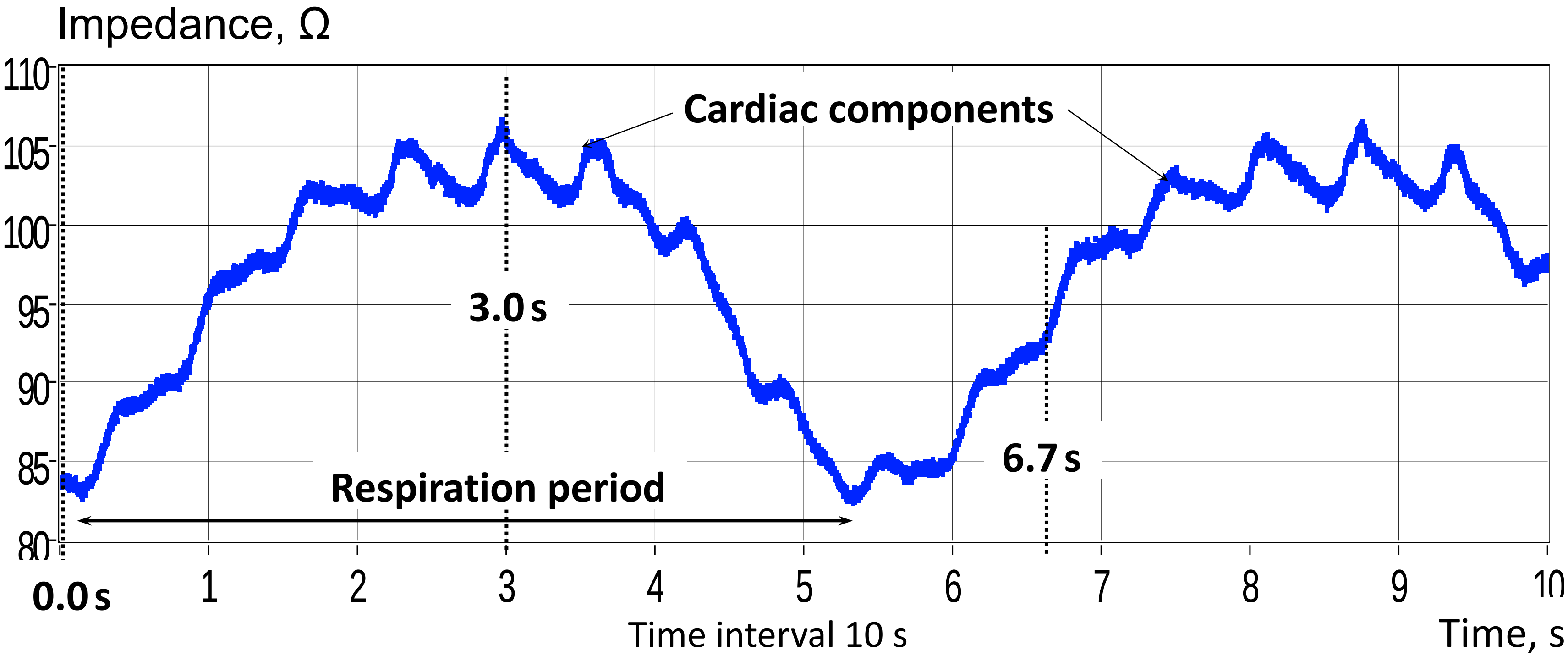
Spectrogram of the time-variant impedance

The complete spectrogram of the impedance magnitude in the 10 second time interval containing cardiac and respiratory variations



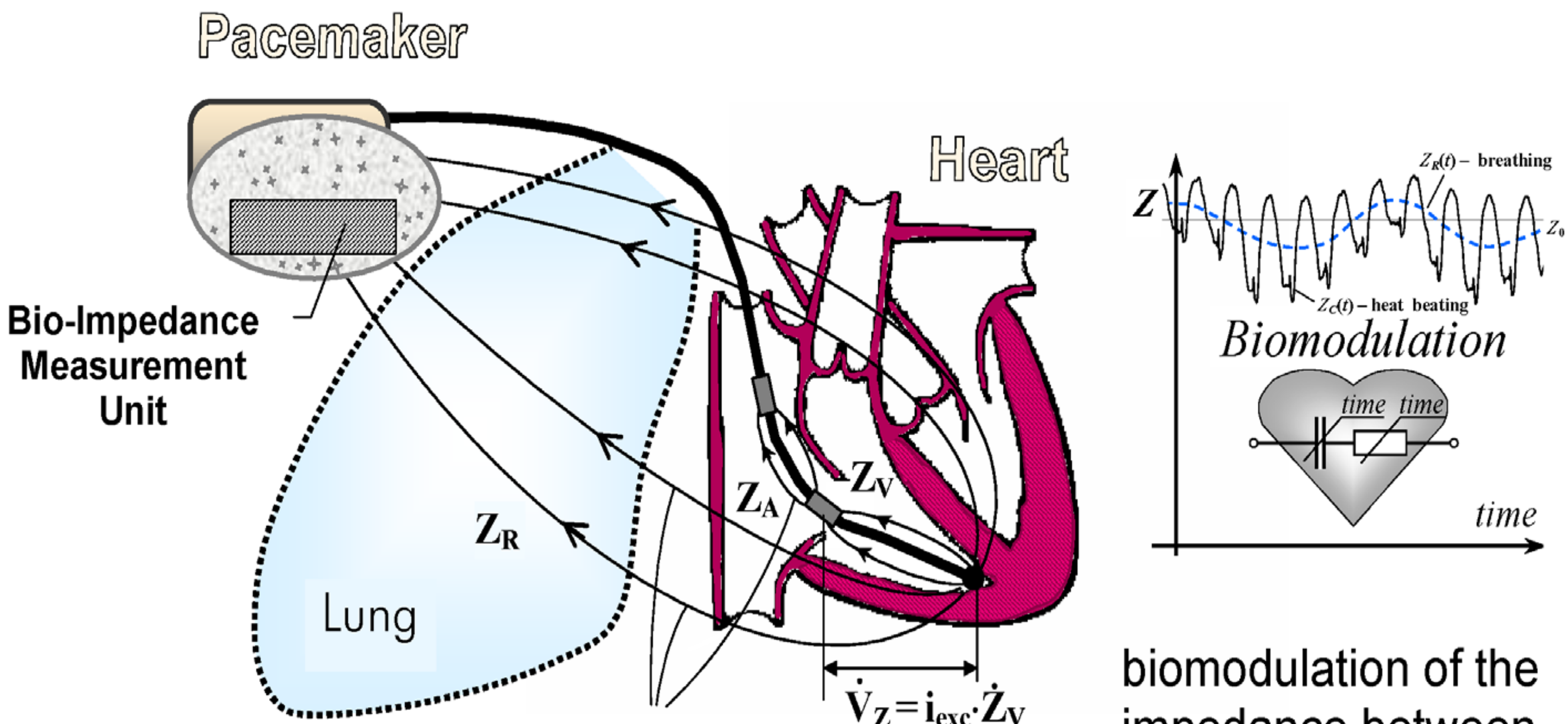
Variations of the impedance magnitude in time

Impedance magnitude variations at 1 kHz frequency, including changes of cardiac and respiratory components



Impedance measurement for pacing rate control

(St Jude Medical, USA, and Smartimplant OÜ, Estonia, owned the patents)



excitation current, i_{exc} = 1 to 10 μA

f_{exc}= 4 to 64 kHZ, typically

biomodulation of the impedance between the tip electrode and pacemaker case

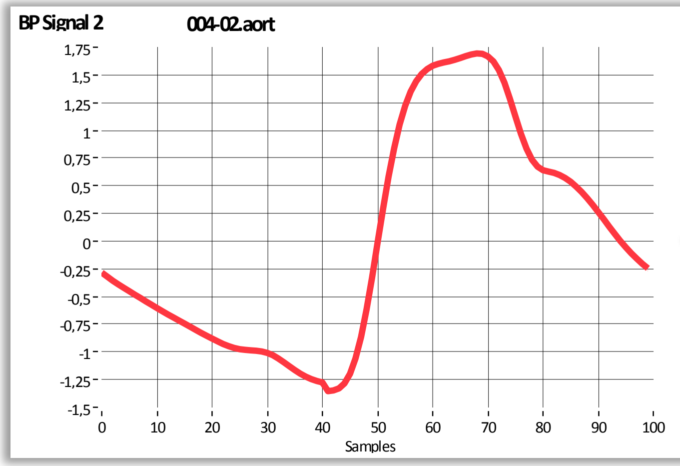
A device for controlling of syringe needles in the body for the point-of-care medicine (cure, electronic biopsy)

Injeq Oy, Finland, bought a licence for using the impedance spectroscopy technology (binary multifrequency)

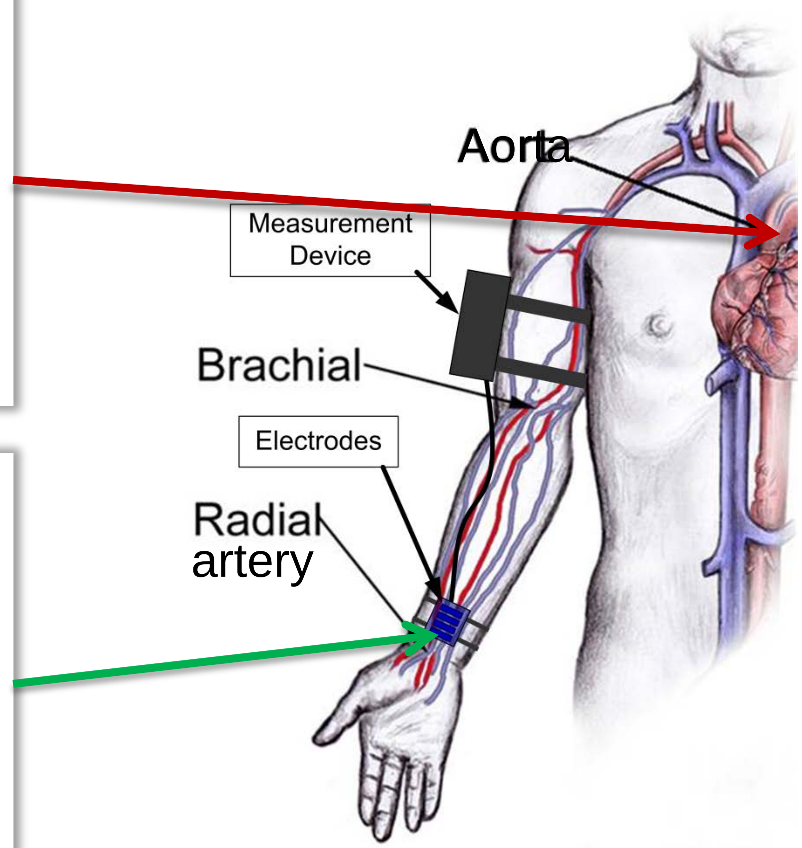
Monitoring of Central Aortic Pressure (CAP) of blood:

recording of waveforms and finding parametres as Augmentation Index
(about 100 human experiments in East-Tallinn Central Hospital)

The CAP waveform (normalized)



Radial EBI waveform (normalized)



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Smart clothes, textile electrodes (LADE OÜ, Estonia):

breathing and heart beating analysis

Impedance spectroscopy sensing in lifejackets

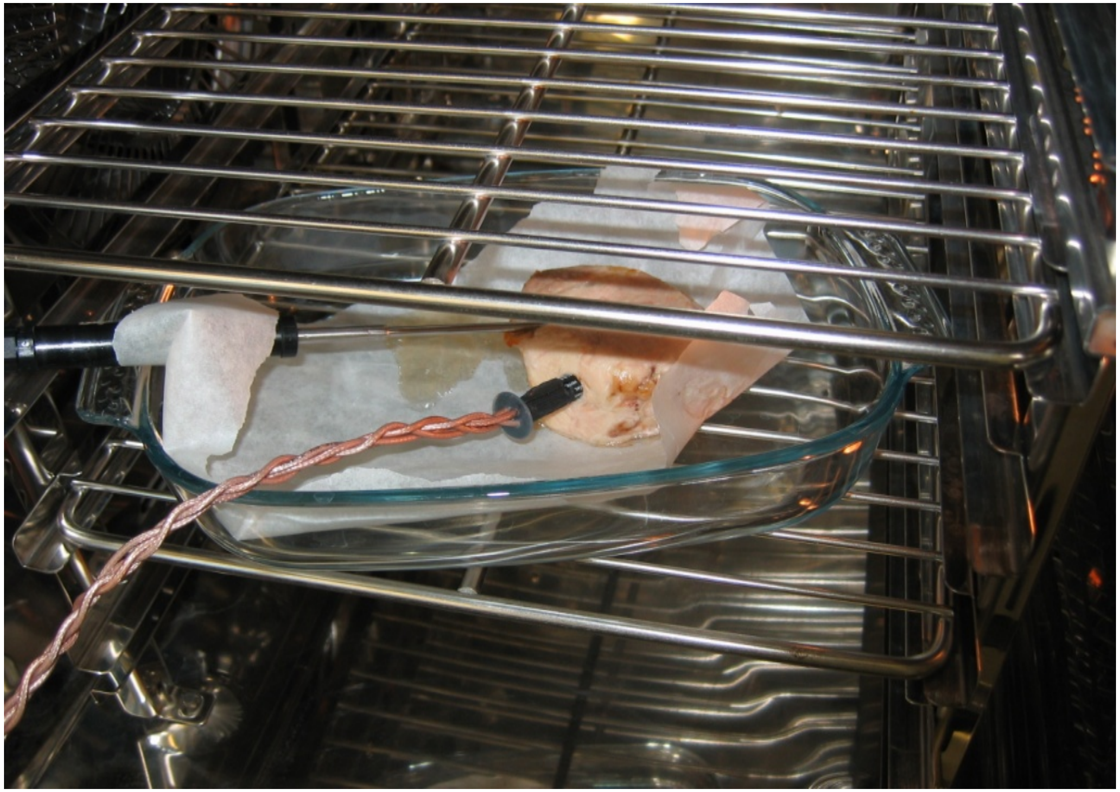
Partners:

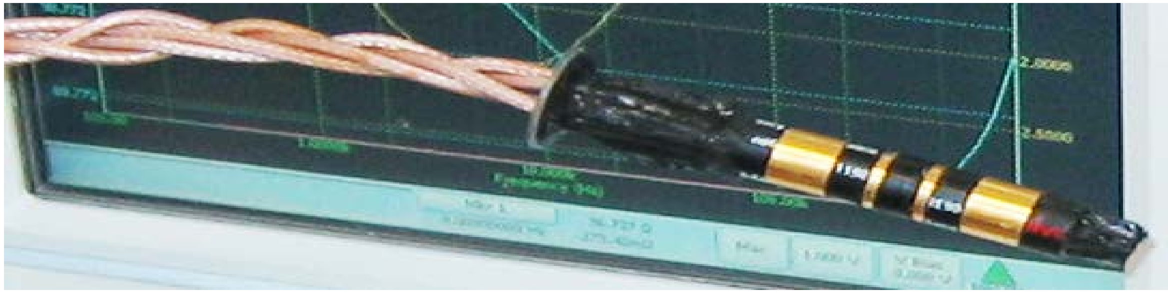
MarinePool (Germany) and LADE OÜ (Estonia).

For the use in Nordic and Polar seas: wireless monitoring of breathing and heart beating, both rate and volume, in a salty cold water.

Assessment and control of the meat cooking process

(Electrolux Italy, 2012)





Meat quality assessment (Carometec A/S, Denmark)

CAROMETEC bought a license to use the impedance spectroscopy method (binary multifrequency) for meat quality assessment

Carometec is a world leader in production of meat quality estimation equipment for the food industry

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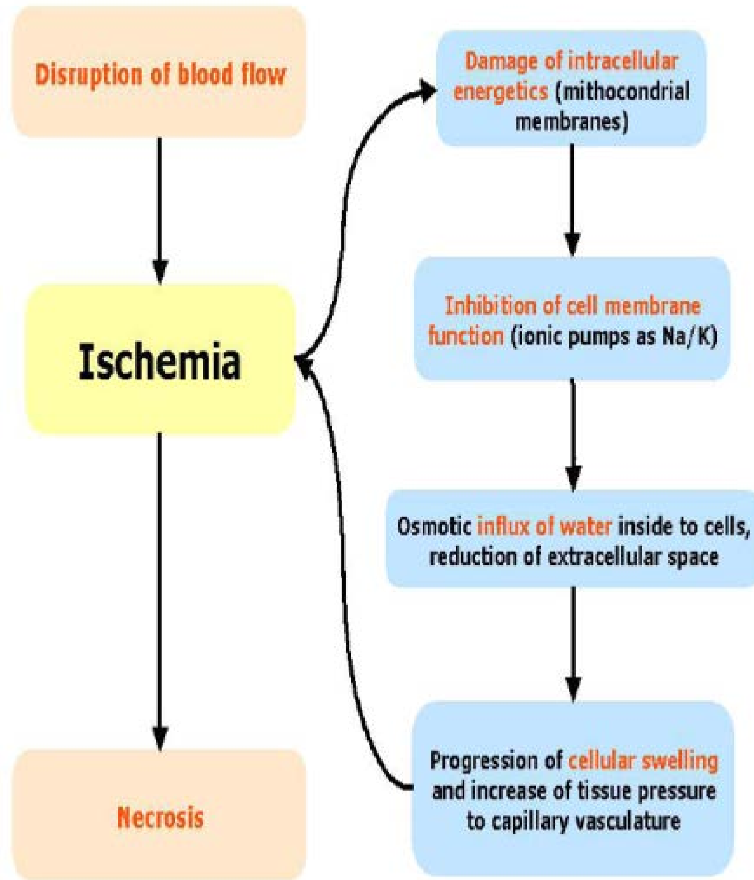
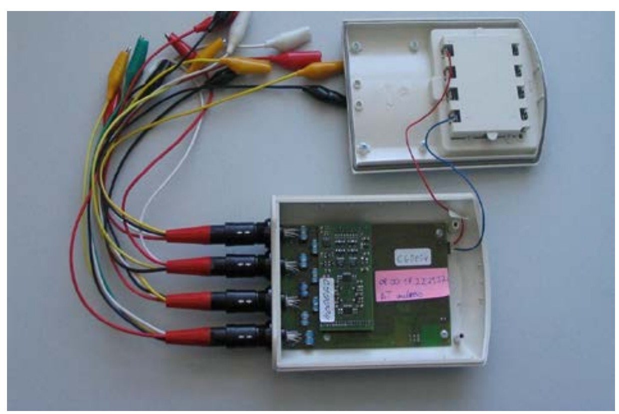
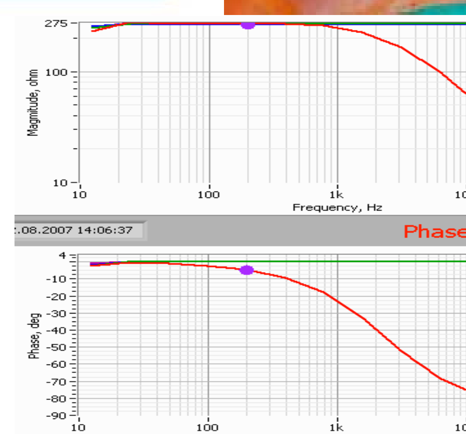
Medical diagnosing in reconstructive surgery (Estonia)

Electrical bioimpedance
of transplanted muscle flaps

"Bioimpedance measurement is a key tool to avoid irreversible muscle damage postoperatively (25% cases)"







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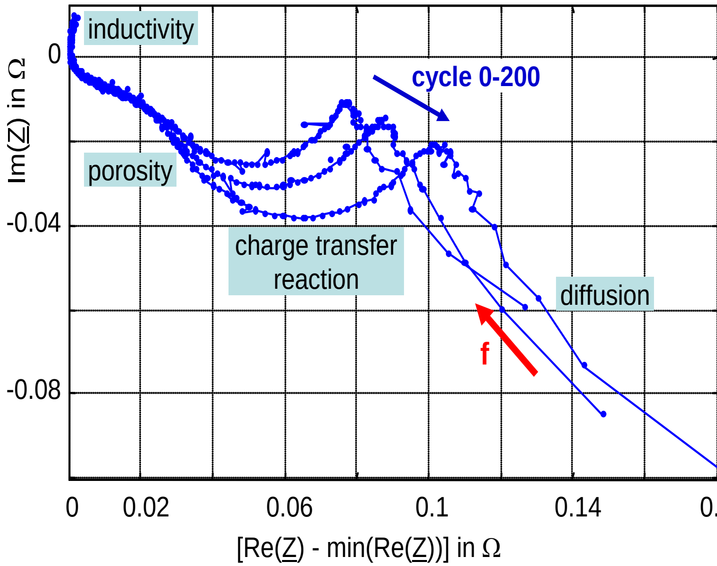
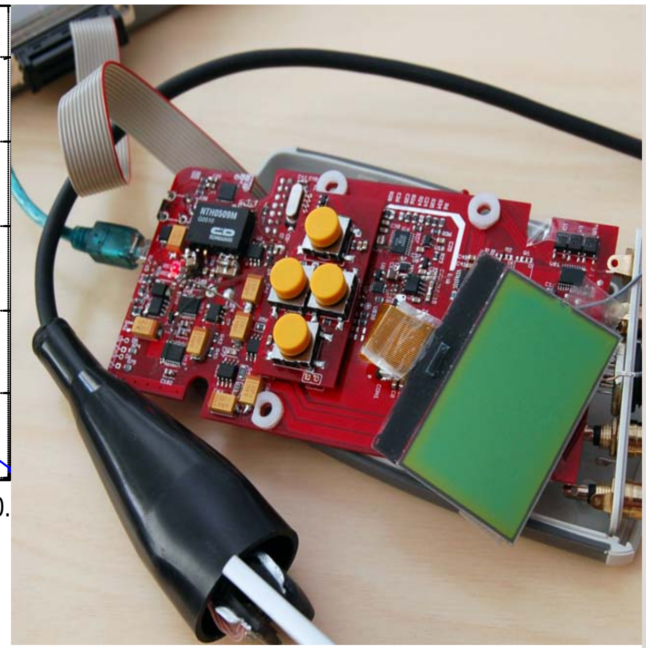
Impedance of electrochemical cells: monitoring the health of batteries





Joint project by:

- Department of Measurement and Automation, University of Bundeswehr Munich
- TJ Seebeck Institute of Electronics at Tallinn University of Technology
- Texas Instruments, USA

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Thank you for listening !

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