*International Journal of Bioelectromagnetism* *www.ijbem.org*
Vol. 17, No. 1, pp. 13 - 19, 2015

# Frequency-optimized rectangular pulses for deep brain stimulation

**Rauno Gordon, Mart Min, Raul Land**
*Thomas Johann Seebeck Department of Electronics, Tallinn University of Technology, Tallinn, Estonia*

Correspondence: R Gordon, Thomas Johann Seebeck Department of Electronics, Tallinn University of Technology, Ehitajate tee 5, 19086, Tallinn, Estonia. E-mail: rauno@elin.ttu.ee, phone +372 6202165, fax +372 6202151

---

***Abstract.*** We propose in this paper that short minimum length rectangular chirp pulses can very effectively be used for neural stimulation or more specifically – for deep brain stimulation. It has been proposed that the ideal frequency window for neural tissue stimulation by microelectrodes lies in the mostly resistive area between the lower frequency electrode interface dispersion and the higher frequency cell membrane dispersion. We demonstrate that the frequency spectrum of the short chirp pulses can be tuned to be exactly in the desired spectrum window. The rectangular short chirp pulses can also be very efficiently generated with undemanding electronics which makes them a very compelling solution for implanted devices using microelectrodes for deep brain stimulation.

*Keywords:* neural stimulation, chirp, rectangular pulse, spectrum, energy-efficient stimulation, impedance, implanted devices, cardiac pacemaking, deep brain stimulation

---

## 1. Introduction

There are many situations in medical practice where patient health is benefited from neural tissue stimulation. So called brain pacemakers are routinely implanted for treatment of epilepsy, Parkinson’s disease and major depression [Samii et.al. 2004]. Cochlear implants are routinely used for mitigating the loss of hearing and retinal implants are used now in medical practice too in case of blindness caused by retinitis pigmentosa or macular degeneration [Brain Research 2013]. Recent discoveries on how the vagus nerve stimulation can be used for treatment of arthritis, ischemia and other inflammatory diseases point to rapidly expanding applications of neural stimulation [Tracey 2007]. Future advances in neural tissue stimulation are additionally expected to treat paralysis caused by injury to the spinal cord or to other parts of the nervous system and could also lead to various cognitive enhancement systems.

Stimulation of neural tissue for treatment purposes needs to be extremely energy efficient for several reasons. The energy input needs to be optimal from physiological reasons because electrodes are small with high impedance and tissue heating can occur because of highly concentrated energy [Mercanzini 2014, Wang and Weiland 2015]. Also the electric charge must be counted with positive and negative electric charge in the alternating signal balancing out exactly without any excess electric charge left in the tissue that could compromise the tissue areas next to the electrodes [Grimnes and Martinsen 2015].

From the technology aspect we want to optimize the energy usage because the devices for neural tissue stimulation are in most practical cases totally implanted and therefore separated from outside power sources. The effects of the treatment must last for years or decades. At the same time the available space for the electronics and battery is very restricted. Therefore we are looking for very simple and efficient electronics for the stimulation pulse generation.

## 2. Methods

It has been proposed that it is most practical to stimulate deep brain tissue with electrical energy concentrated into the resistive region in the impedance spectrum that lies above the low frequency electrode polarization effects and below the cell membrane effects manifested at higher frequencies [Mercanzini 2014, Wang and Weiland 2015]. Depending on the electrode size and application area, the frequency band for electrode polarization can extend up to 1kHz or even 10kHz [Grimnes and Martinsen 2015]. It is known that dielectric dispersion of tissue impedance due to cell membranes can normally start from 100kHz to 1MHz but can be lower too depending on the tissue [Grimnes and Martinsen 2015].

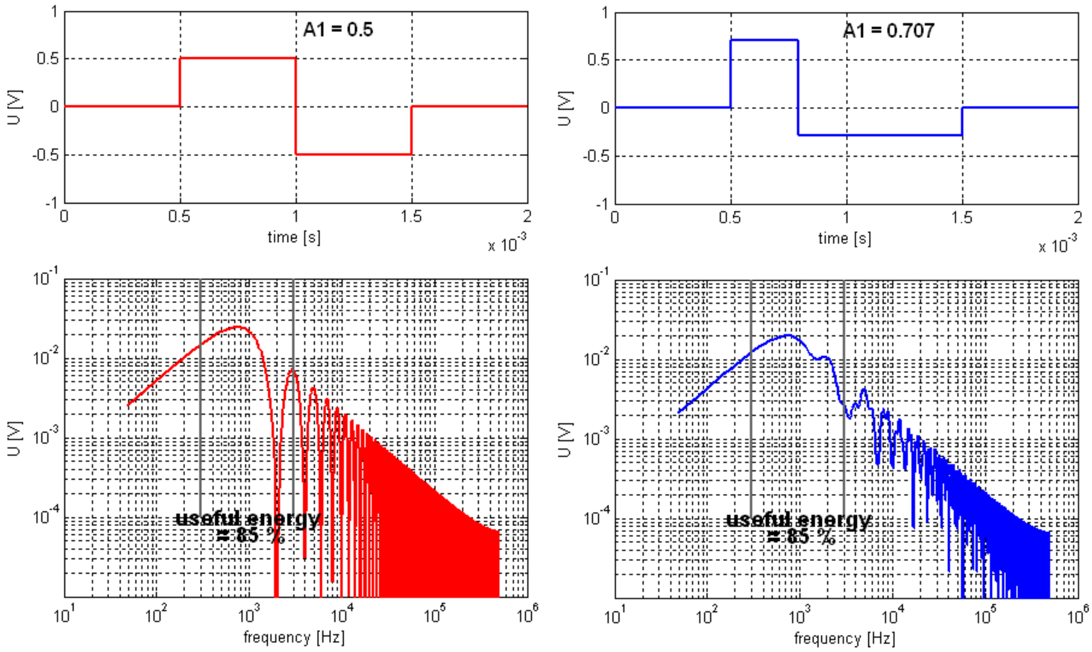

***Figure 1.*** *Balanced rectangular pulses with the ratios of excitation/balancing amplitudes of 0.5 and 0.707 (1/√2) with the respective spectra given below.*

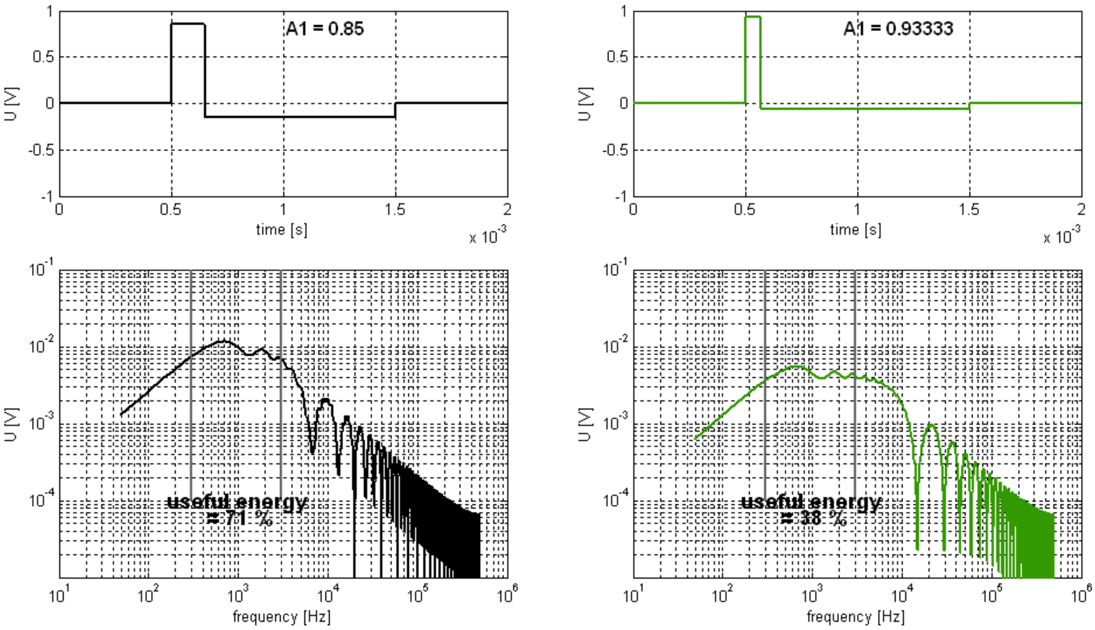

***Figure 2.*** *Balanced rectangular pulses with the ratios of excitation/balancing amplitudes of 0.85 and 0.93333 with the respective spectra given below.*

We tested the type of minimum length rectangular pulses that are currently used in implanted devices [Butson and McIntyre 2007]. All signals were 1ms long rectangular signals with charge-balance that has equal positive and negative voltage*time area. The tests included signals from equal length positive-negative pulses to also common 1:15 ratio for time and amplitude. And the tests also included pulses with a gap between the excitation and balancing pulses (Fig. 3 and 4) [Butson and McIntyre 2007].

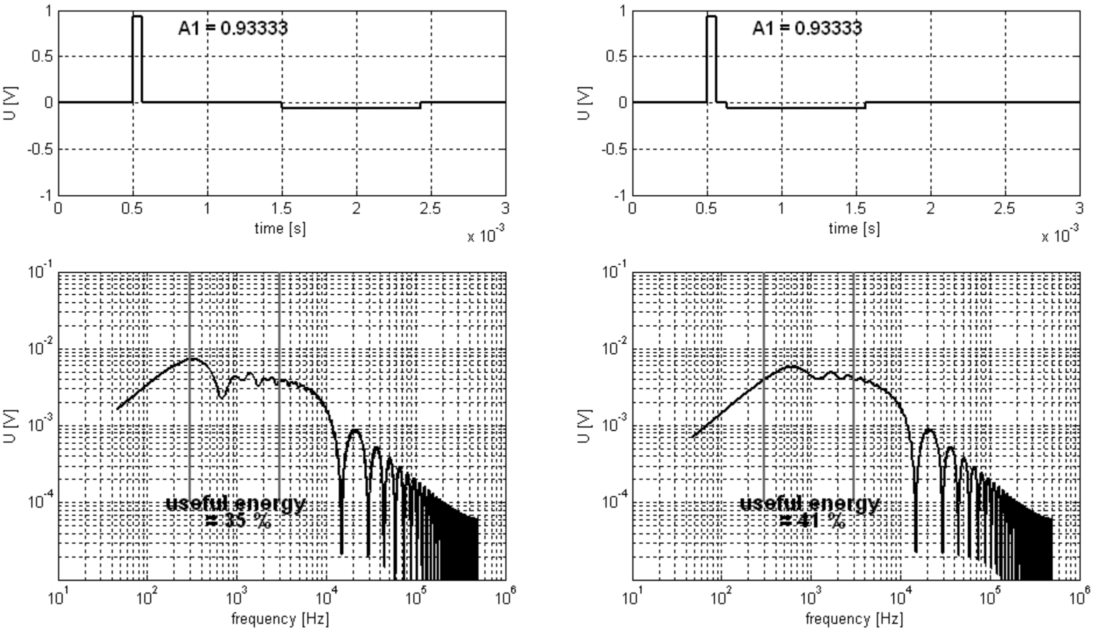

*Figure 3.* *Balanced rectangular pulses with the ratios of excitation/balancing amplitude of 0.93333 with a large gap (length of balancing pulse) on the left and with small gap (length of excitation pulse) on the right. Spectra of both signals are shown below.*

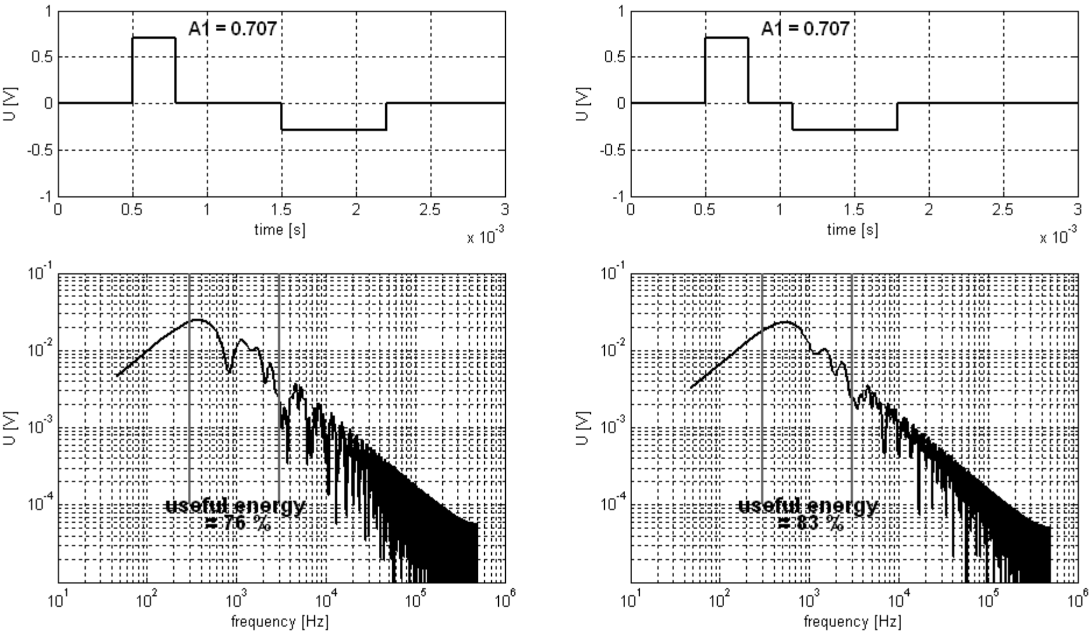

*Figure 4.* *Balanced rectangular pulses with the ratios of excitation/balancing amplitude of 0.707 (or 1/√2) with a large gap (length of balancing pulse) on the left and with small gap (length of excitation pulse) on the right. Spectra of both signals are shown below.*

Frequency spectrum of the pulses was calculated with FFT as single pulses with zero padding of 10ms before and after the pulse (approximately 10 times the pulse length). The pulse duration of 1ms was chosen for best illustrative purposes, where pulse durations can be evidently shown as 0.5/0.5 or with some other ratio. The frequency band of 300Hz to 3kHz was chosen as one decade in the range, where the illustrative signal had peak energy. The ratio of pulse energy within the one decade band was determined separately from the whole signal energy for comparison.

For comparison we also added a quarter-period sine-wave chirp, where the frequency rises during first quarter of the sinus signal period with the function of $t^2$ and then drops with the same function (Fig. 5) [Paavle et.al. 2011, Min et-al. 2015]. Comparison with complicated but flexible short chirp excitation can be used for evaluation of energetic effectiveness of the proposed rectangular pulses. In general, the chirp expresses as a sine wave signal $C(t)$ with changing instantaneous frequency $\omega(t) = d\theta(t)/dt = 2\pi f(t)$:

$$C(t) = A\sin\theta(t) = A\sin\{\int \omega(t)dt + \theta_0\} \tag{1}$$

The simplest but most known is linear chirp, the frequency of which rises (or declines) proportionally with time. More complicated, as exponential, logarithmic, power or arbitary function chirps are used for obtaining different specific shapes of their spectra. For example, the n-th power chirp (frequency expresses as $f^{\,n}$) with initial frequency $f_o$ and initial phase $\theta_o = 0$ can be expressed as

$$C_n(t) = A\sin\left(2\pi\left(f_0 \cdot t + k_{\mathrm{ch}}\, t^{n+1}/(n+1)\right)\right), \tag{2}$$

in which the chirping rate $k_{\mathrm{ch}} = (f_{\mathrm{fin}} - f_0)/T_{\mathrm{ch}}^{\mathrm{n}}$. Duration of n-th power excitation is as follows:

$$T_{\mathrm{ch,n}} = \frac{(n+1)p}{n \cdot f_0 + f_{fin}} \tag{3}$$

In Fig. 5 is given a short quadratic function (n = 2) chirp with initial frequency $f_o = 300$ Hz and final frequency $f_{\mathrm{fin}} = 3000$ Hz, reaching only a quarter (p = 1/4) of the full cycle ($\max\theta = \pi/2$) and then retrieving back to its initial value $\theta = 0$. The same pulse with negative sign follows to balance the injected charge.

## 3. Results

The signal waveform and its FFT calculated spectrum with energy ratio in 1-decade are shown for 0.5/0.5 and 0.707 amplitude ratio pulses in Fig. 1. Pulses with the higher – 0.85 and 0.93333 – ratios are shown in Fig. 2 with their respective spectra.

We also tested the spectrum energy density with signals that have a pause or gap between the excitation pulse and balancing pulse. The gap with the right duration between the excitation pulse and balancing pulse can significantly increase the efficiency of stimulation [Hofmann et.al. 2011]. Signals with 1:15 ratio for duration and amplitude, and with longer and shorter gap are shown in Fig. 3. Signals with a lesser ratio of 0.707 and also with larger and smaller gap are shown in Fig. 4. Spectra calculated with FFT are added to the figures and energy percentage in the 1-decade range of 300Hz to 3kHz is calculated as well.

For comparison, we also added a quarter-period sine-wave chirp, where the frequency rises during first quarter of the sinus signal period and then drops with the same function (Fig. 5 and 6) [Paavle et.al. 2011, Min et.al. 2015]. The spectrum of this signal drops very rapidly with higher frequencies after the peak. Although the energy calculation does not show a larger energy efficiency in one decade, the fast drop in higher frequencies allows this to be used as an extremely energy efficient signal for slightly wider spectrum band. This is one of the most energy-efficient signals in narrow spectrum band there is.

The comparison results showed that the best signals for energy-efficiency were with equal time and amplitude. But the high energy efficiency (over 80% in the 300Hz-3kHz band) was also exhibited by pulses with down to $1/\sqrt{2}$ ratio of excitation/balancing pulses (Fig. 1). Below that threshold and with the ratio of 1:15 – which is commonly proposed for excitation – the energy efficiency in limited spectrum was considerably less.

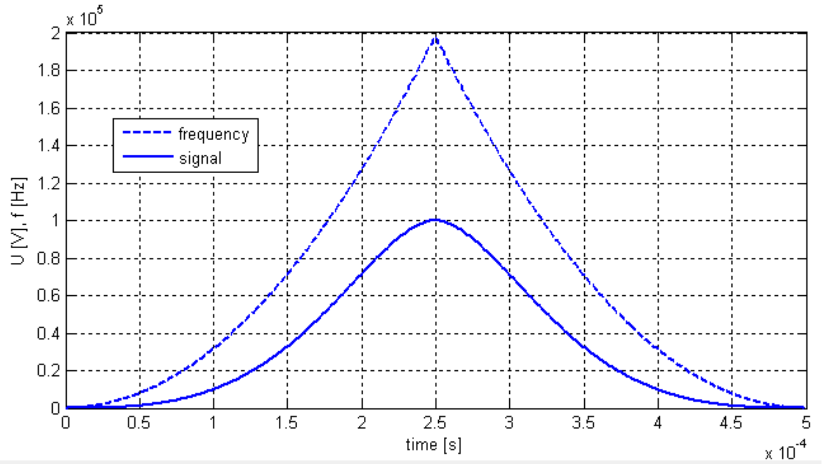

***Figure 5.*** *A short sine-wave chirp signal where the frequency rise happens only within one-quarter period and then the similar frequency drop follows. Dashed line represents the frequency (rises up to 200kHz) while the solid line describes the short chirp signal.*

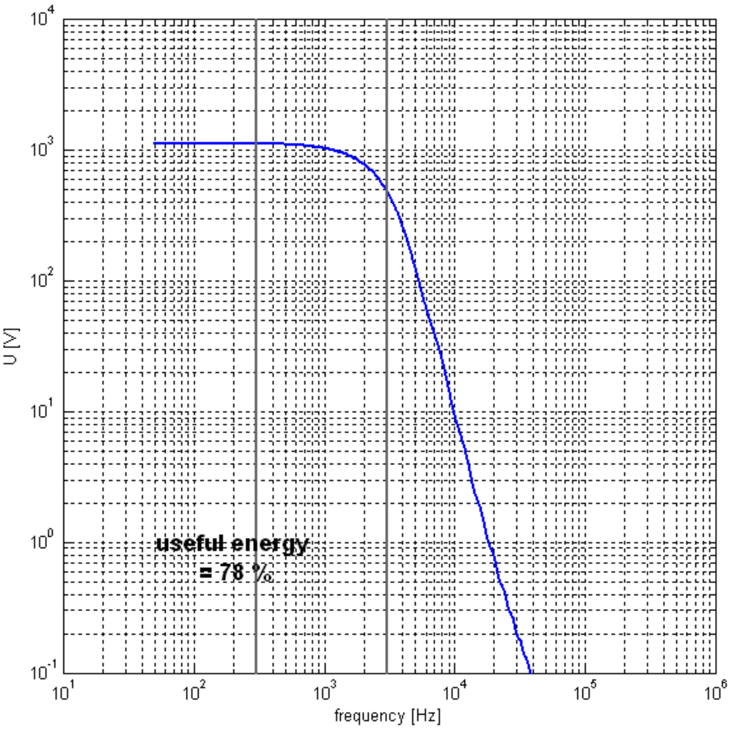

***Figure 6.*** *Spectrum with energy calculation for the sine-wave chirp signal.*

We therefore propose more research in stimulation of the deep brain with rectangular waveforms that have the ratio of $1/\sqrt{2}$ between excitation and balancing pulse amplitude and duration. Those pulses are very energy-efficient and easy to produce with implantable electronics. Those pulses can easily be optimized to have excitation energy in the right frequency spectrum window. In the minimum configuration the signals can consist of only one positive rectangular pulse and one negative pulse immediately after that for charge balancing (Fig. 1). Energy efficiency of 85% can be gained when the short bandwidth of 1 decade is desired. The pulse can also feature a gap between the excitation and balancing parts that is commonly used [Butson and McIntyre 2007]. The gap has certain physiological benefits for excitation and it does not worsen the energy-efficiency in spectrum too much – introducing a short gap of excitation pulse length to the signal with 0.707 ratio did not significantly lower the energy density of the signal (with still 83% of total energy in the 1-decade spectrum band).

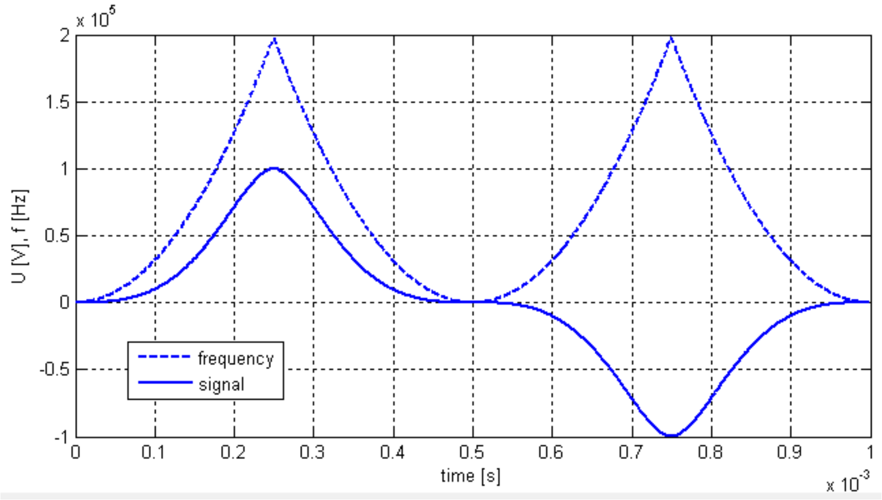

***Figure 7.*** *A shor sine-wave chirp signal with negative balancing part added. Dashed line represents the frequency (rises up to 200kHz) while the solid line describes the short chirp signal with positive and negative balanced parts.*

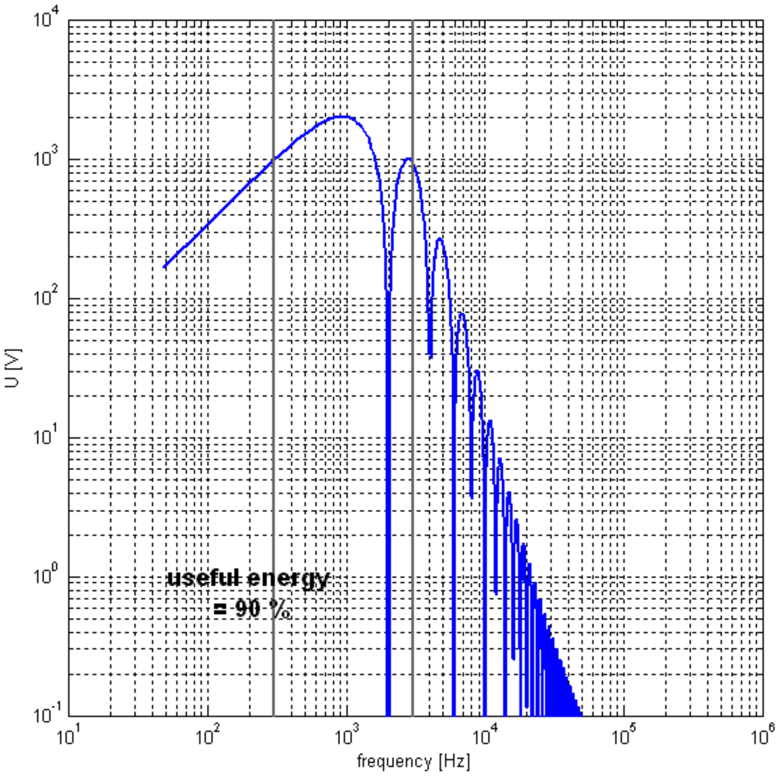

***Figure 8.*** *Spectrum with energy calculation for the balanced sine-wave chirp signal.*

We demonstrated with pulses of 1ms duration here but the central frequency can be readily adjusted to get the peak energy into the desired spectrum band. It just needs the right pulse duration but keeping the same ratio between excitation/balancing pulses that we determined in this work.

We have demonstrated before that the spectrum of these minimum length rectangular pulses is concentrated into a frequency window of limited width [Paavle et.al. 2012]. The frequency spectrum of these pulses can be concentrated into a narrow band with optimizing the pulse durations and positive/negative amplitudes. This optimization can be performed for the electrode and tissue combination at hand for maximally efficient stimulation.

The quarter-period sine-wave chirp signals (Fig. 5, 6, 7, 8) on the other hand give a very promising frequency spectrum. The positive pulse only (Fig. 5) has a unique spectrum in the world of short pulses – it has very fast and smooth decline in energy above the peak frequency. The balanced version of that sine-wave chirp (Fig. 7, 8) has a similar fast decline although with more complex shape. The energy of the balanced quarter-period sine-wave chirp can be concentrated with even higher efficiency than with the rectangular pulses – around 90% of the energy can be concentrated into one decade of frequency band. It is therefore a very efficient way for neural stimulation but the electronics associated with those signals are a bit more complicated for implanted applications.

## 4. Discussion

From the figures 3 and 4 it is evident that shortening the gap between excitation and balancing pulse focusses the energy better into the desired frequency band. This gives guidelines for choosing the right gap between the pulses. On a more general note the minimum length rectangular chirp pulses are clearly a very efficient way to stimulate neural tissue from the point of view of limiting the energy into a narrow frequency band.

The sine-save chirp pulses (Fig. 5, 6, 7, 8) offer an even more focused spectrum and we aim to investigate the use of those types of signals for implanted neural stimulation further.

### Acknowledgements

This research was supported by the European Union through the European Regional Development Fund in the frames of the center of excellence in research CEBE, competence center ELIKO, of the Competence Centre program of Enterprise Estonia and National Development Plan for the Implementation of Structural Funds Measure 1.1 project 1.0101.01-0480.

### References

Samii A, et al. (2004). Parkinson's disease. Lancet, 363(9423): 1783–1793.

BRAIN RESEARCH supported by the European Union 2007-2012. Luxembourg: Publications Office of the European Union, 2013. ISBN 978-92-79-26513-6 doi:10.2777/18131.

Tracey KJ. Physiology and immunology of the cholinergic antiinflammatory pathway. Journal of Clinical Investigation. 2007;117(2):289-296. doi:10.1172/JCI30555.

United States Patent no.: 8,788,042 B2. Apparatus and Method for Optimized Stimulation of a Neurological Target. Mercanzini et al. Date of Patent: Jul. 22, 2014

Wang B, Weiland J. Analysis of the Peak Resistance Frequency Method for Extracting Tissue Resistance from Impedance Spectroscopy. Transactions on Biomedical Engineering TBME-00269-2015.

Bioimpedance and Bioelectricity Basics (Third Edition). Grimnes S, Martinsen ØG. 2015 Elsevier Ltd. ISBN: 978-0-12-411470-8.

Butson CR, McIntyre CC. Differences among implanted pulse generator waveforms cause variations in the neural response to deep brain stimulation. Clinical Neurophysiology 118 (2007) 1889–1894.

Paavle T, Min M, Parve T. Aspects of Using Chirp Excitation for Estimation of Bioimpedance Spectrum, Fourier Transform - Signal Processing, Dr Salih Salih (Ed.), ISBN: 978-953-51-0453-7, InTech, 2012. Available from: http://www.intechopen.com/books/fourier-transform-signal-processing/aspects-ofusing-chirp-excitation-for-estimation-of-bioimpedance-spectrum

Hofmann L, Ebert M, Tass PA, Hauptmann C. Modified pulse shapes for effective neural stimulation. Frontiers in Neuroengineering. 28 September 2011 doi: 10.3389/fneng.2011.00009.

Paavle T, Min M, Trebbels D. Low-Energy Chirps for Bioimpedance Measurement. In: Proc. of 34th International Conference on Telecommunication and Signal Processing (IEEE Catalog No CFP1188P-CDR), Budapest, Hungary, August 18-20, 2011. IEEE, 398 - 402.

Min M, Parve T, Pliquett U. Impedance detection. In: Encyclopedia of Microfluidics and Nanofluidics. (Ed. Prof. Dongqing Li), ISBN 978-1-4614-5488-5, Springer, New York, 2015, pp 1338-1361.