Precise Frequency-Pattern Analysis Reveals the Functional Structure of Complex Systems

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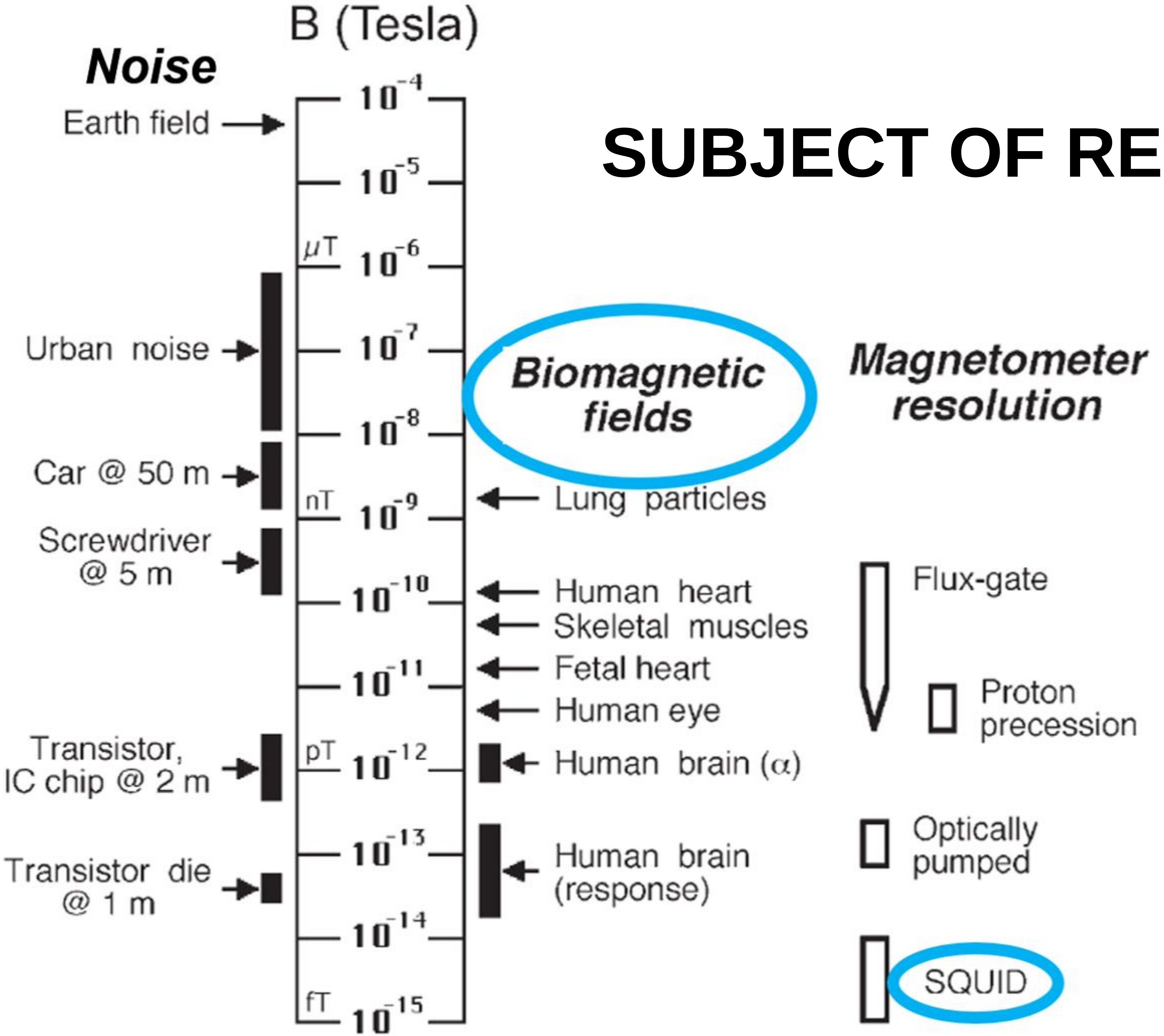
SUBJECT OF RESEARCH



RESEARCH OBJECTIVE

Reconstruction of the locations and time courses of the complex system components from the magnetic field of this system.

Function of the system is considered as a production of magnetic field.

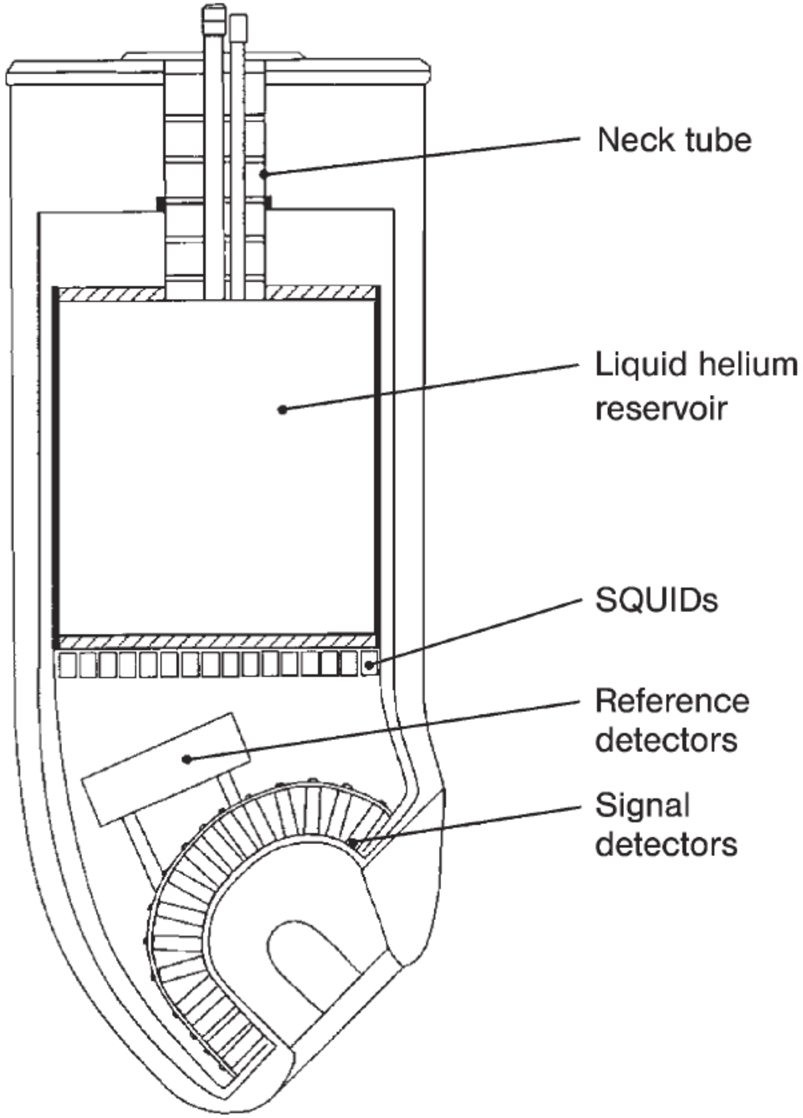
Functional structure – spatial distribution of electrical or magnetic components.

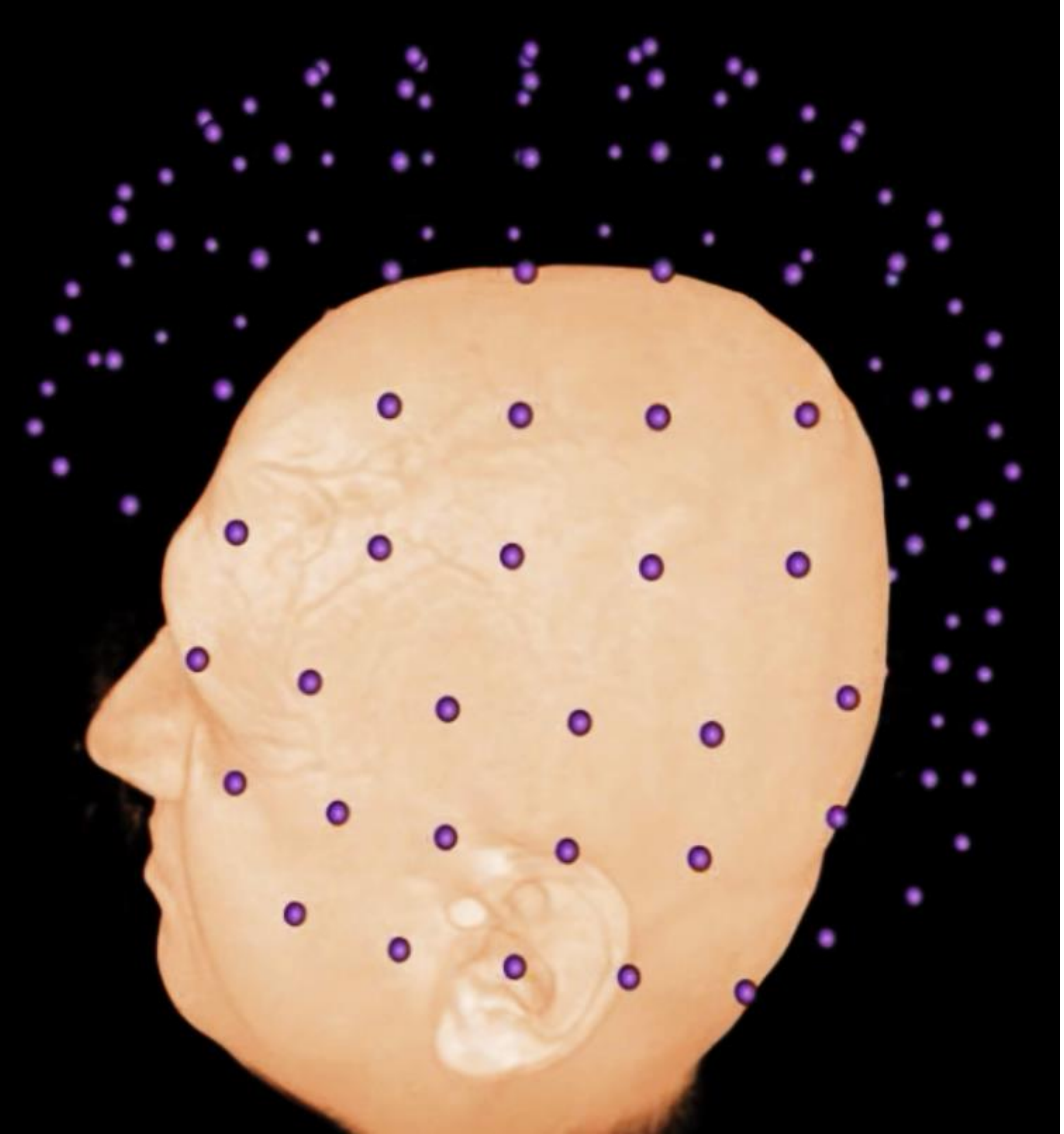
INSTRUMENTS AND METHODS

The experimental data were obtained on three devices:

- Head shaped gradiometer of the first order, 275 channels, VSM Medtech, installed in the New York University Center for Biomagnetism, New York, USA
- Planar gradiometer of the second order, 36 (9x4) channels, Cryoton Co. LTD, installed in the Kotel'nikov Institute of Radio-engineering and Electronics, Moscow, Russia
- Planar gradiometer of the second order, 7 channels, Cryoton Co. LTD, installed in the National Research Center “Kurchatov Institute”, Moscow, Russia
- Methods of data analysis were developed in the Institute of Mathematical Problems of Biology RAS, Pushchino, Russia

Magnetoencephalograph: cryogenic sensors at liquid He temperatures in magnetically shielded room

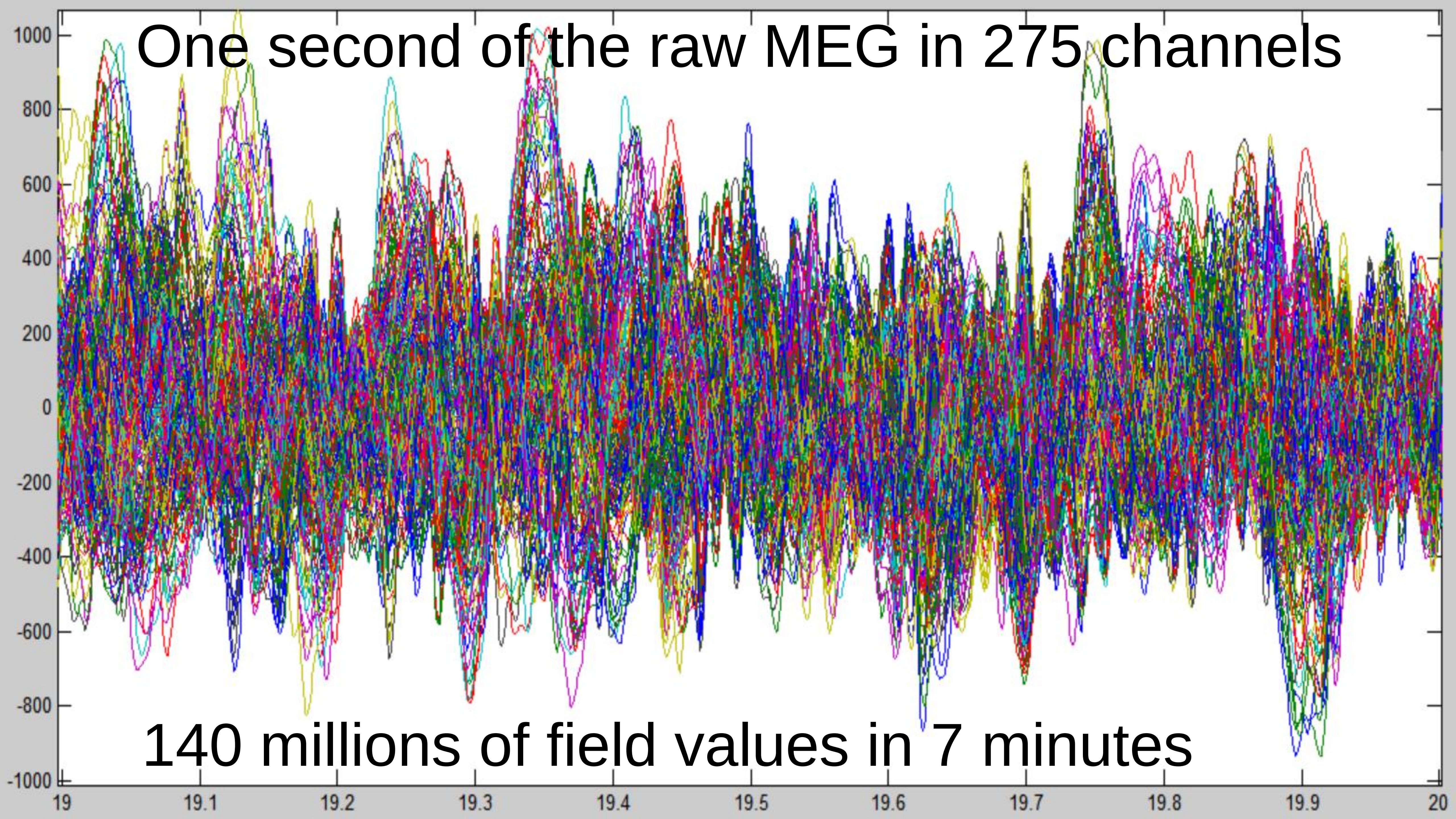




Magnetic Encephalography

general layout of the experiment

Gradiometer sensors around the head of the subject.



One second of the raw MEG in 275 channels
140 millions of field values in 7 minutes
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
19
19.1
19.2
19.3
19.4
19.5
19.6
19.7
19.8
19.9
20

The multichannel Fourier transform calculates a set of spectra for experimentally measured functions $\tilde{B}_k(t)$

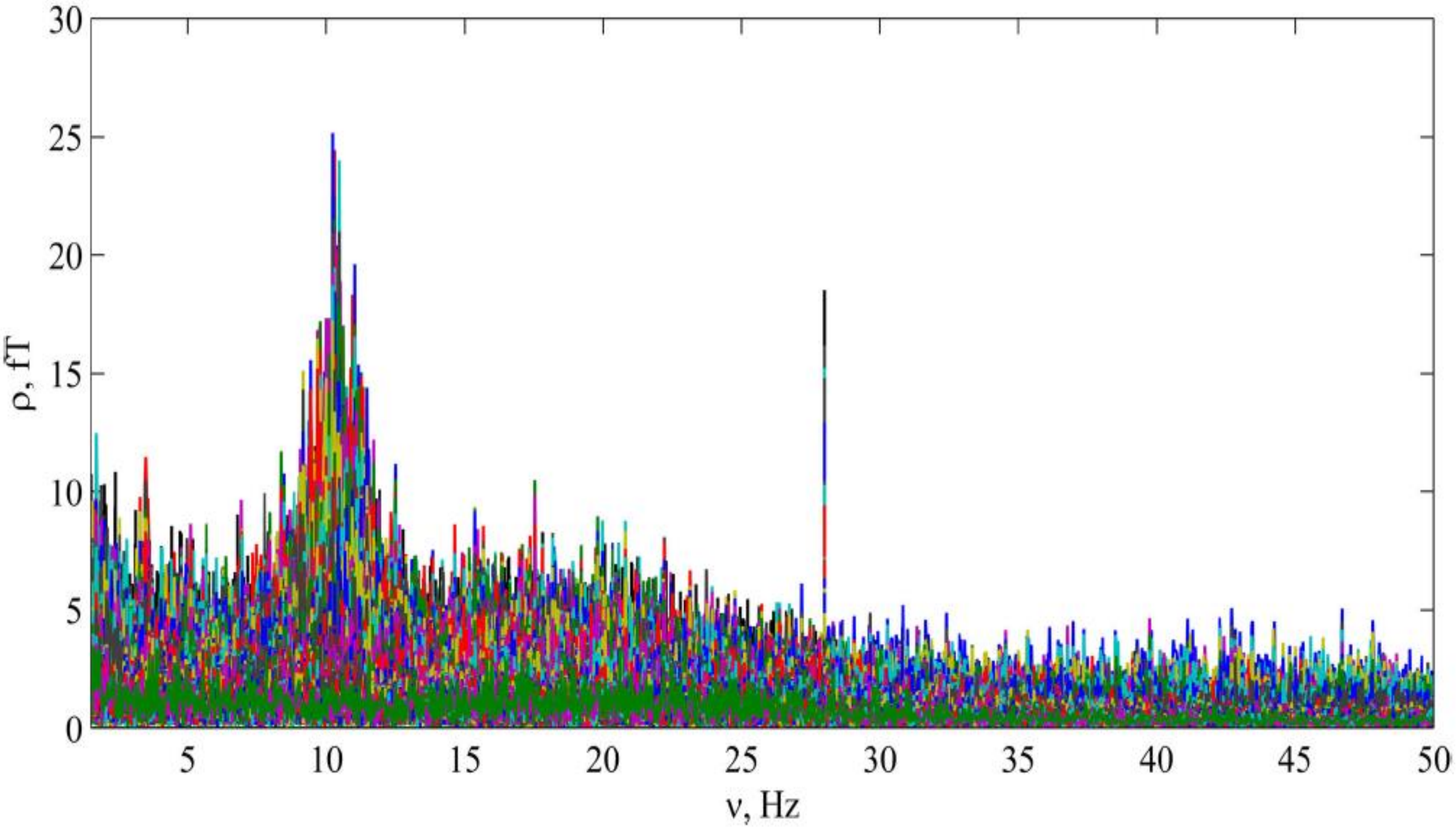
$$a_{0k} = \frac{2}{T}\int_0^T \tilde{B}_k(t)dt,\ a_{nk} = \frac{2}{T}\int_0^T \tilde{B}_k(t)\cos(2\pi\nu_n t)dt,$$

$$b_{nk} = \frac{2}{T}\int_0^T \tilde{B}_k(t)\sin(2\pi\nu_n t)dt,$$

$$B_k(t) = \frac{a_{0k}}{2} + \sum_{n=1}^{N} \rho_{nk}\sin(2\pi\nu_n t + \varphi_{nk}),\quad \nu_n = \frac{n}{T},\quad N = \nu_{\max}T,$$

$$\rho_{nk} = \sqrt{a_{nk}^2 + b_{nk}^2},\ \varphi_{nk} = \operatorname{atan2}(a_{nk}, b_{nk})$$

MULTICHANNEL FOURIER SPECTRUM OF THE MAGNETIC ENCEPHALOGRAM



Inverse Fourier transform for each frequency

$$B_{nk}(t) = \rho_{nk} \sin(2\pi \nu_n t + \varphi_{nk}),$$

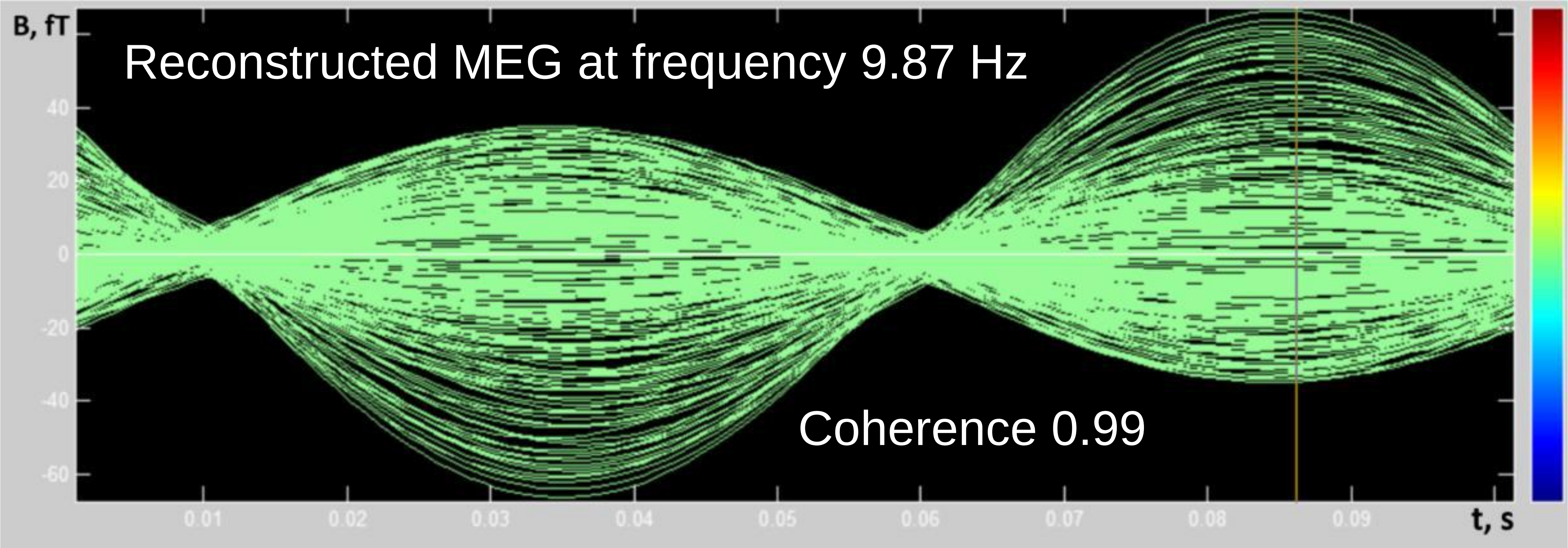
$$t \in [0, T_{\nu_n}], k = 1, \ldots, K$$

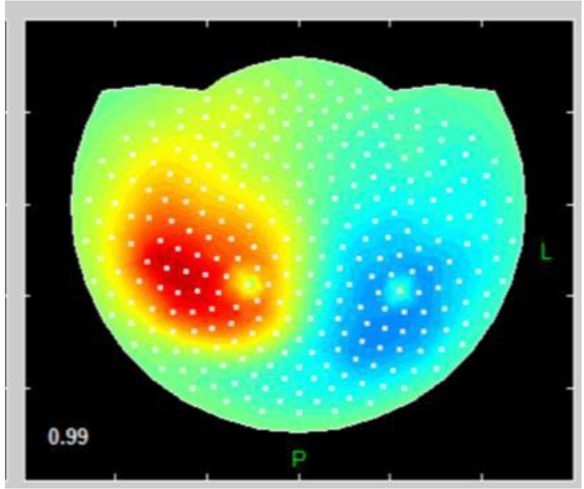
$$T_{\nu_n} = \frac{1}{\nu_n}$$

Coherent oscillation provides separation of time and space

$$B_{nk}(t) = \rho_{nk} \sin(2\pi \nu_n t + \varphi_n)$$

Field pattern ρ_{nk} oscillates as a whole at frequency ν_n

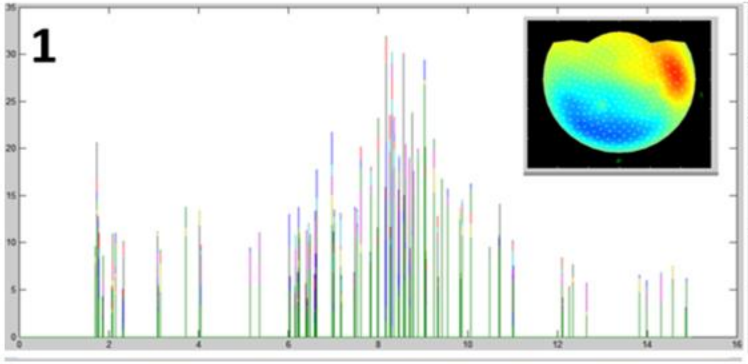


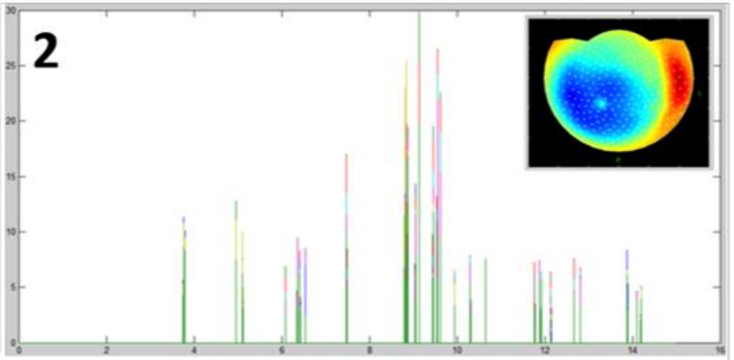


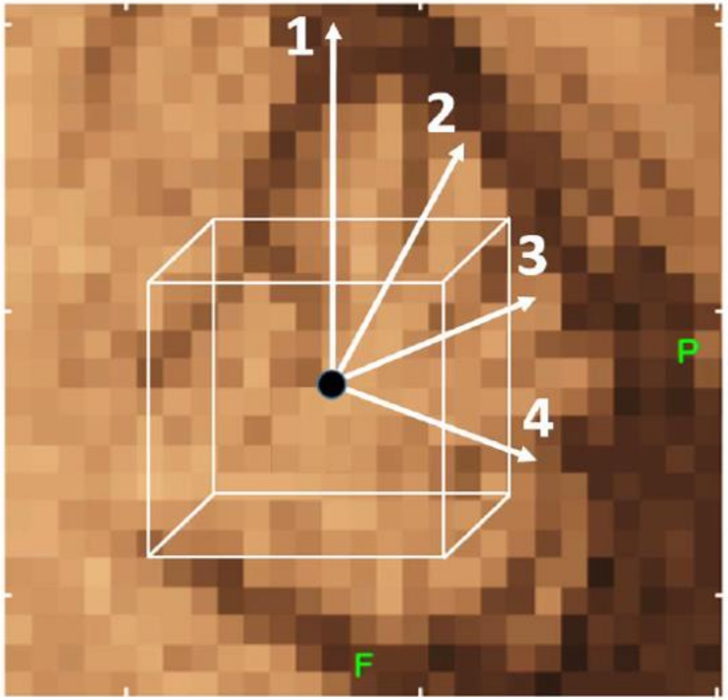
Reconstructed
field pattern
at frequency 9.87 Hz

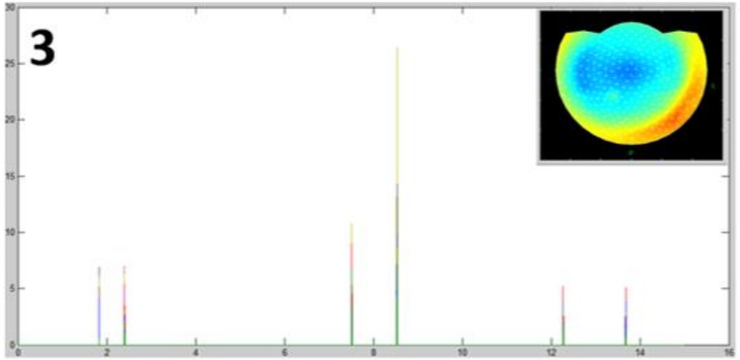
Massive inverse problem solution by exhaustive search

In the volume
25x25x25 cm^3
with the step 3 mm
over 2 millions
of trial patterns
are calculated

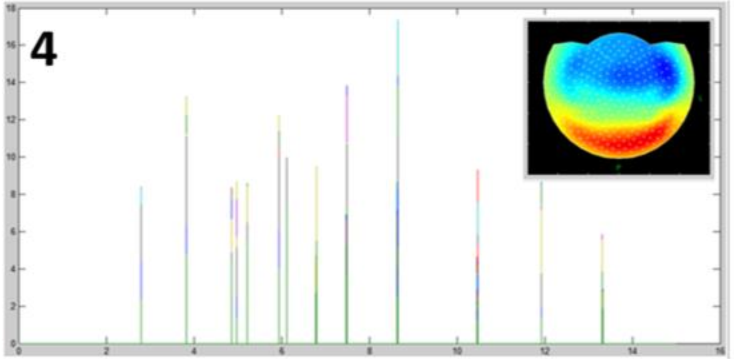




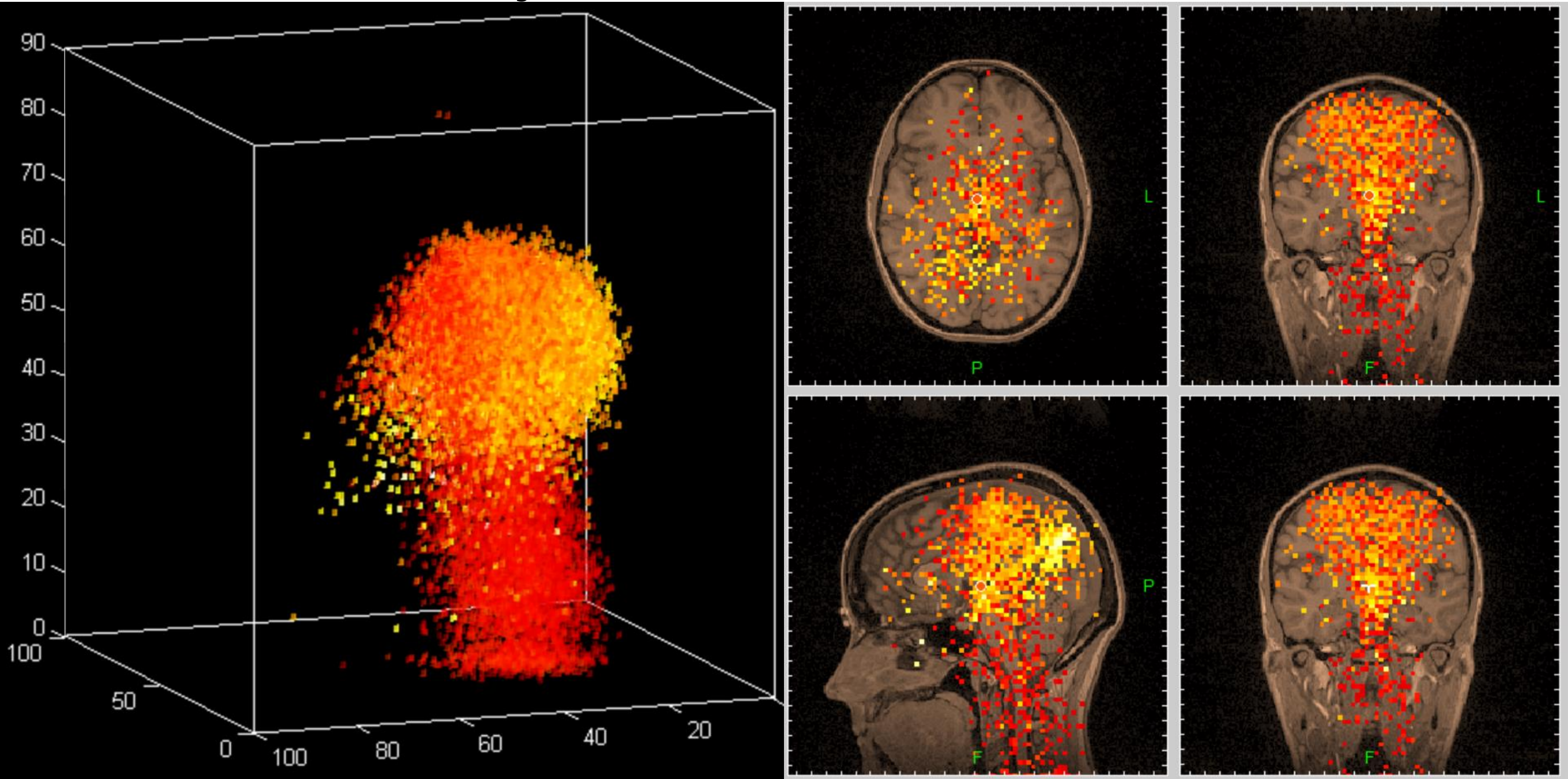


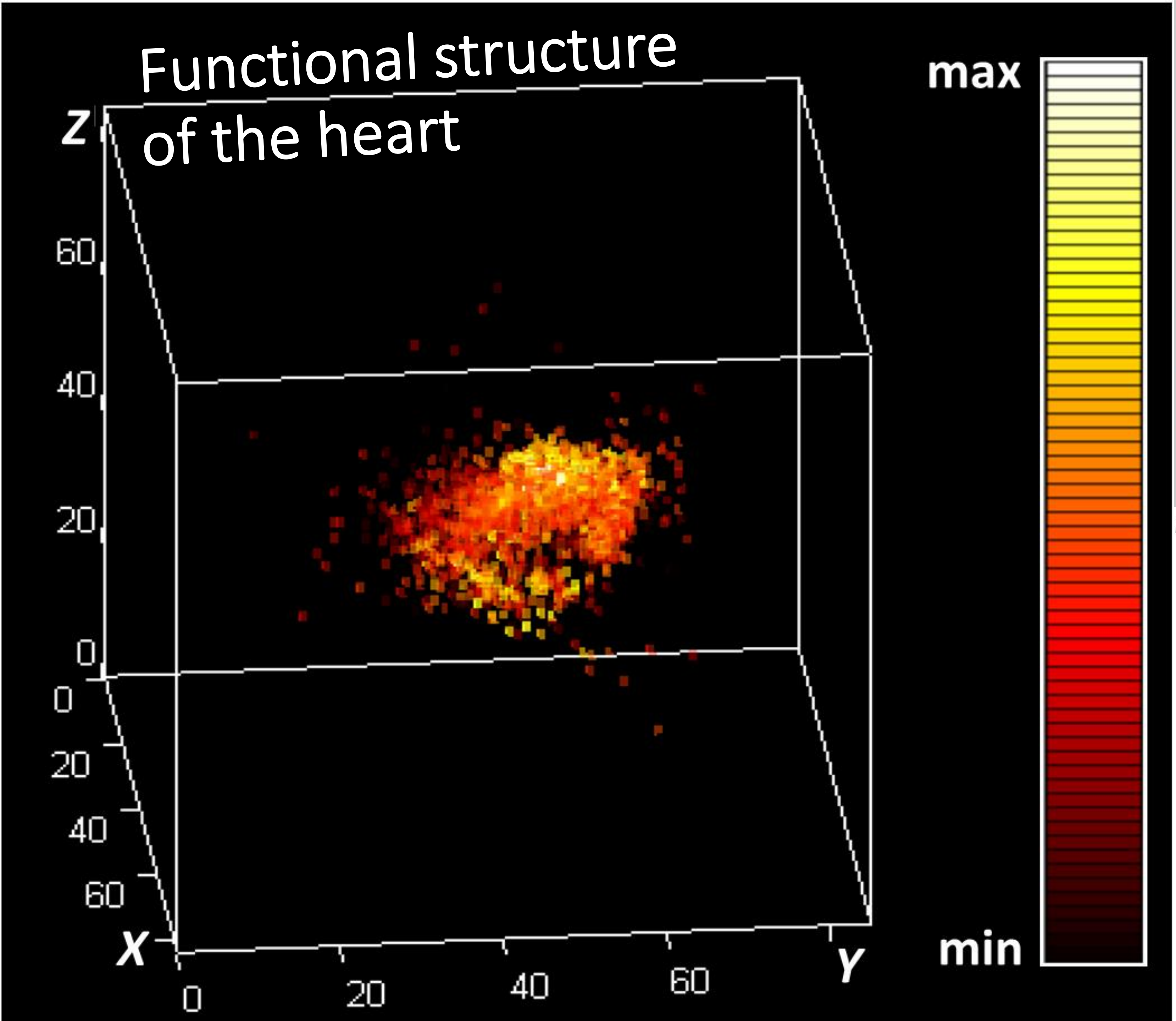


Trial dipoles in one voxel, field patterns and partial spectra

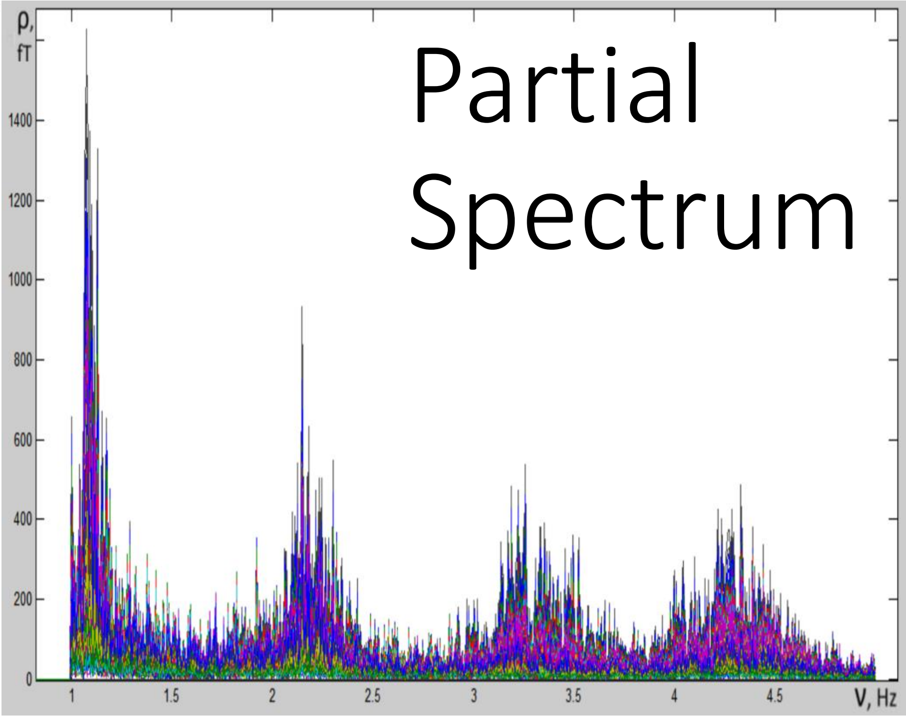


Head and neck functional tomogram, frequency band 0-100 Hz, shown over the subject's MRI

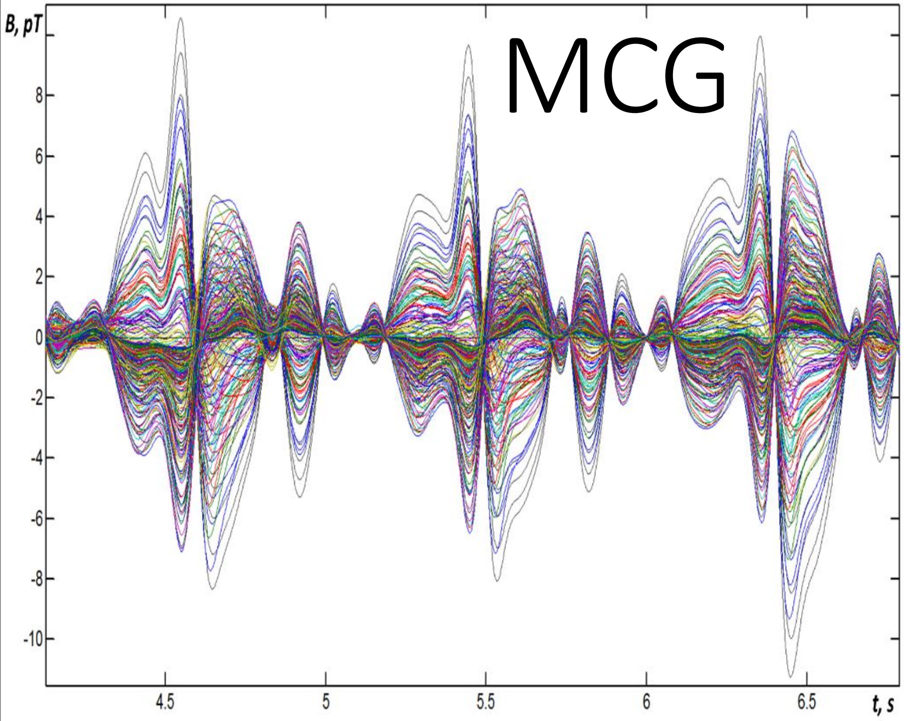




Functional structure
of the heart
Z
60
40
20
0
0
20
40
60
X
0
20
40
60
Y
max
min

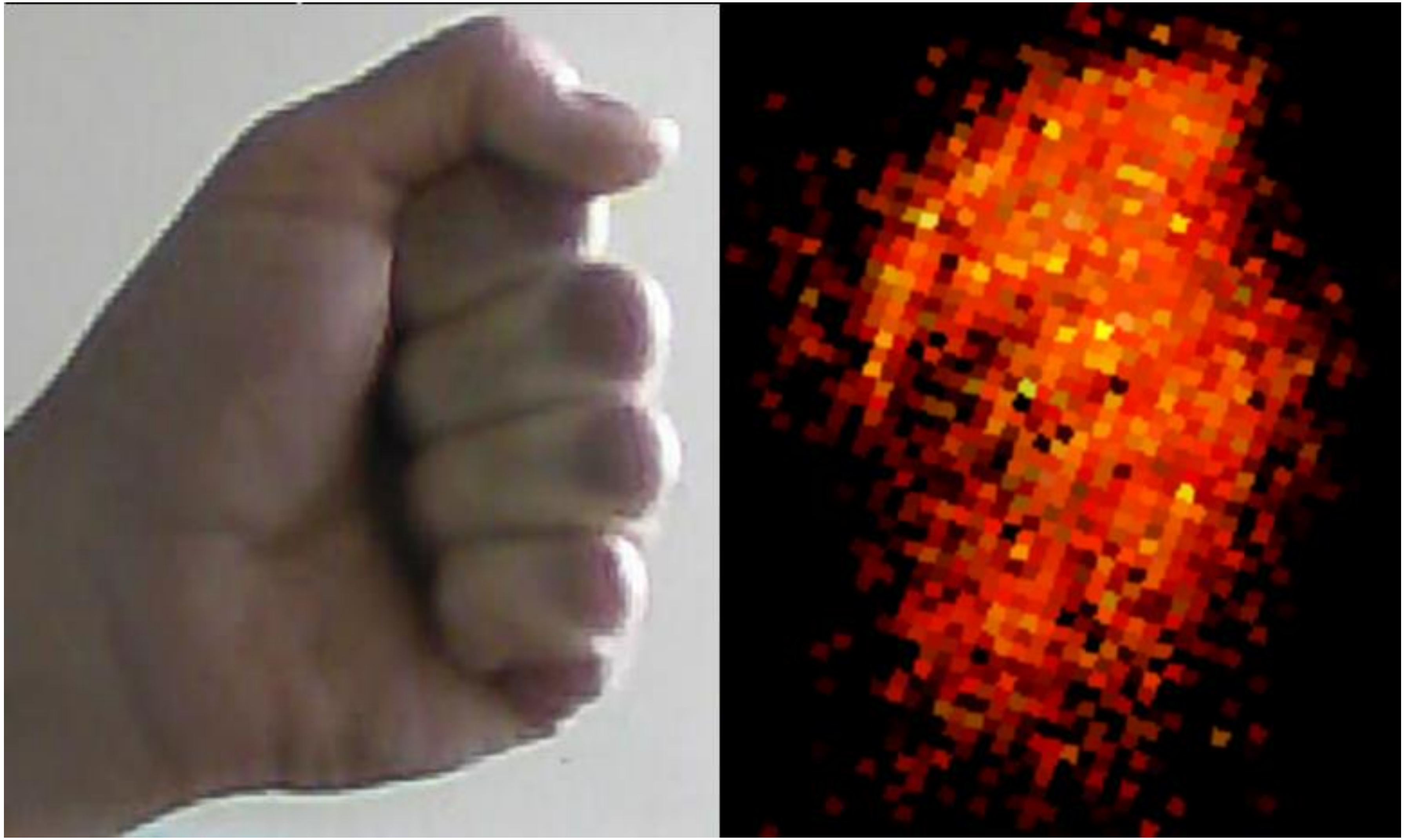


Partial
Spectrum
ρ, fT
ν, Hz

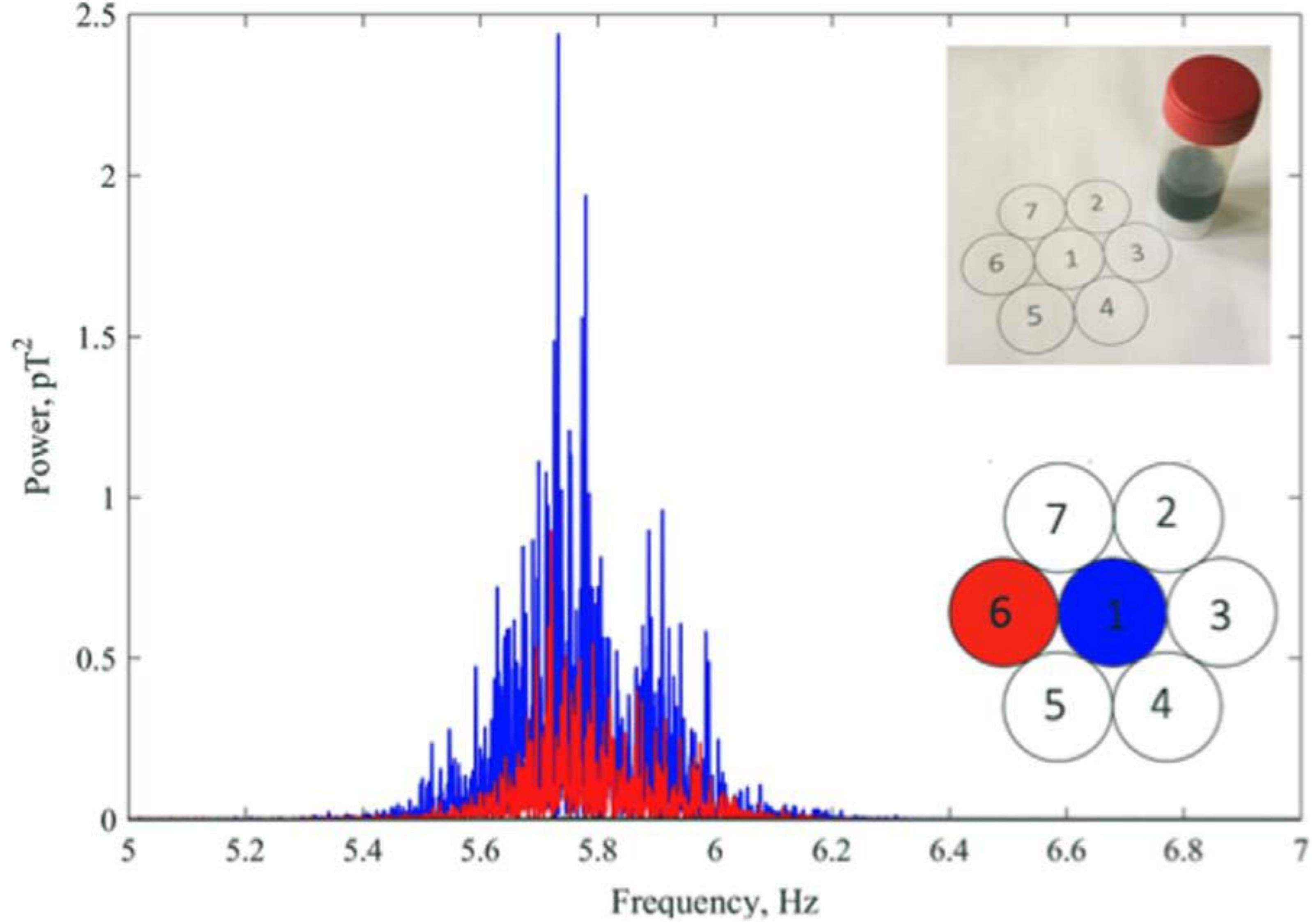


MCG
B, pT
t, s

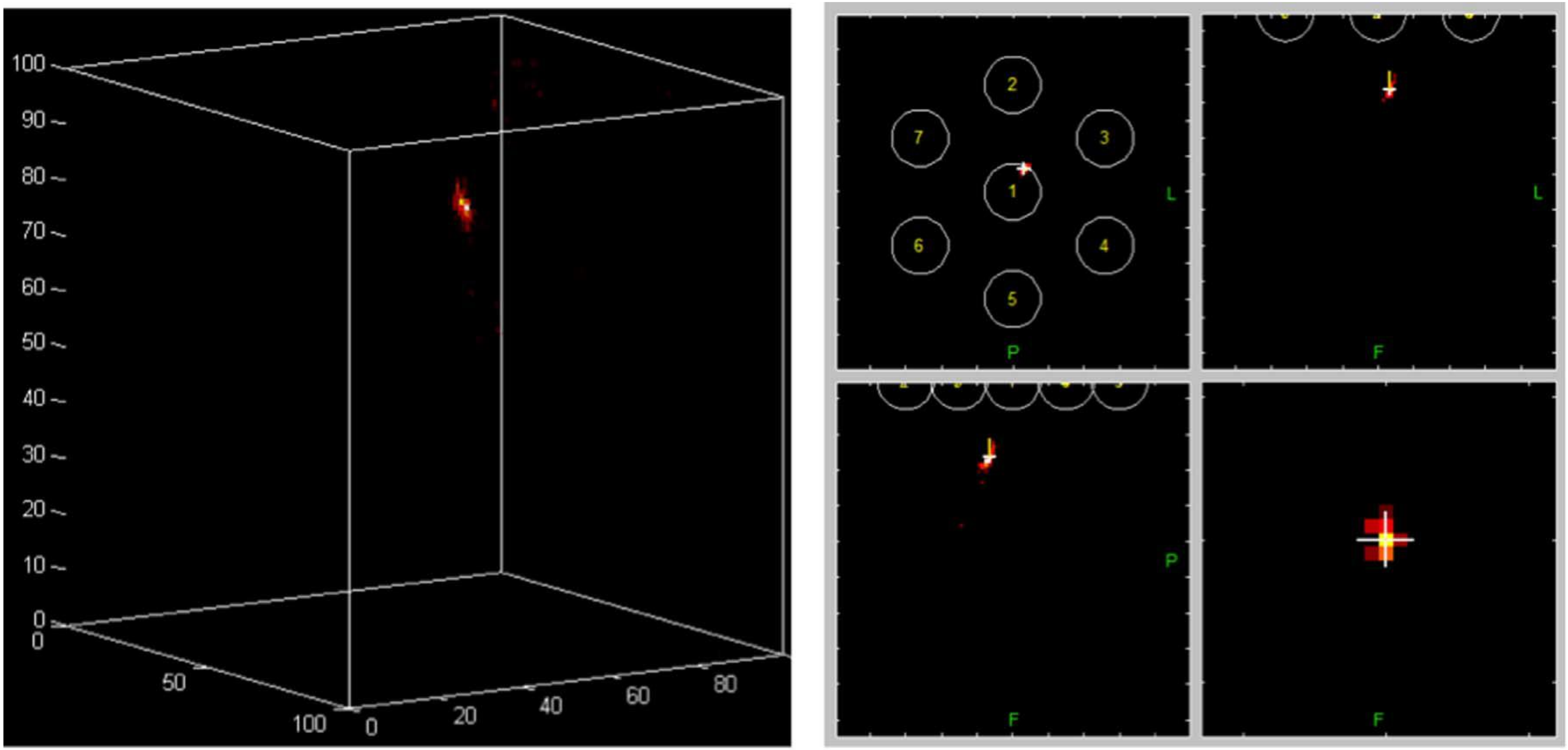
Functional structure of the hand



3D imaging of magnetic particles using the 7-channel magnetoencephalography device without pre-magnetization or displacement of the sample



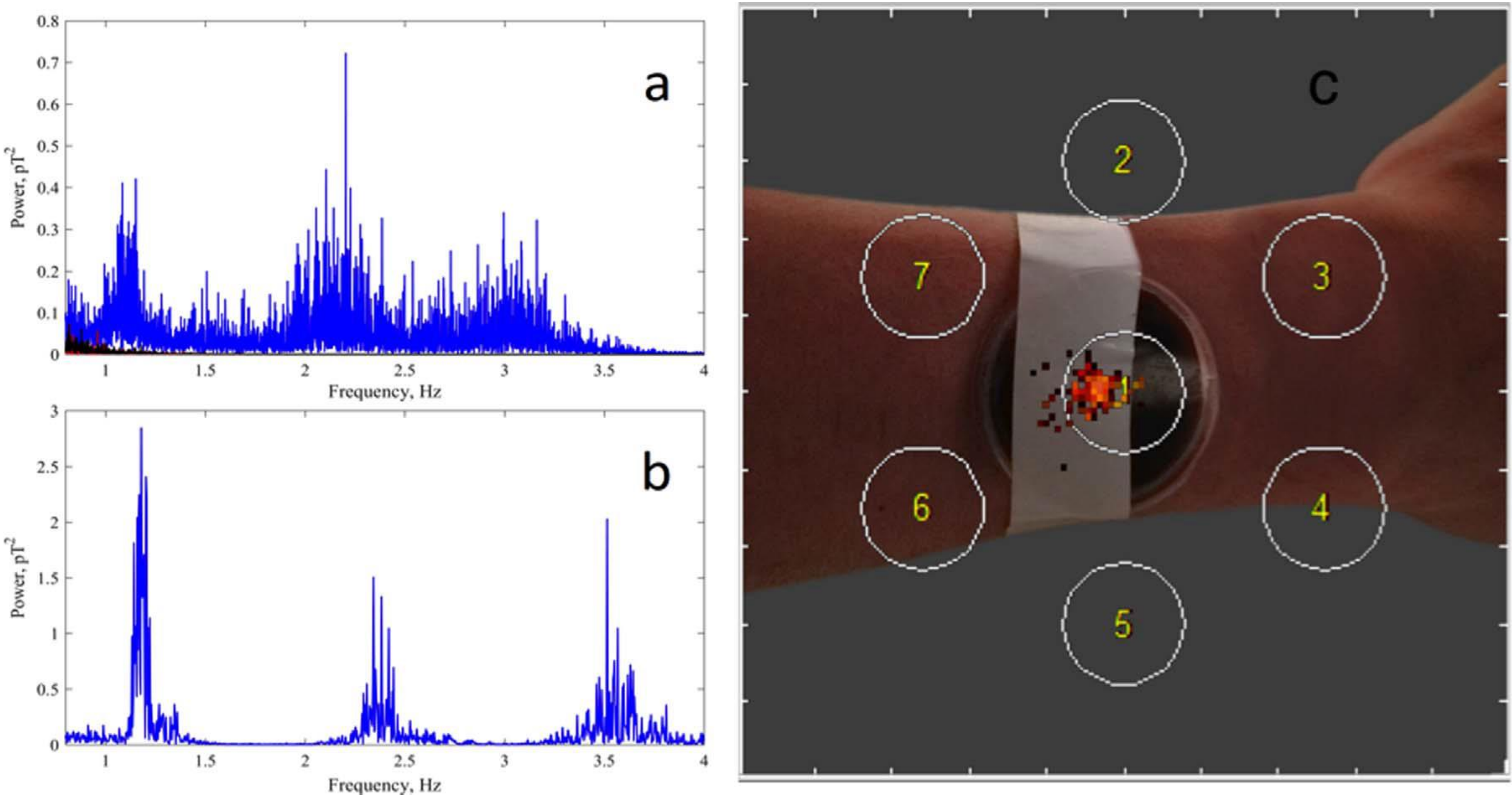
The spectra of the noise generated by the vial with the ferrofluid, situated under channel 1 (blue) and channel 6 (red) of the MEG device.
Black – the spectrum of the noise without vial, less than 1% of maximal power.



3D-view of the source of magnetic noise and its tomographic sections. Also shown is the measuring device (the planar set of seven sensors) and an enlarged section through the object. The brightness of each voxel corresponds to the total power, located at this voxel.

a - Spectra of the ferrofluid in Petri cup, attached to the hand (blue) and of the hand without ferrofluid (black);

b - Spectrum of the magnetic cardiogram, registered by the same device;



c - Localization of the magnetic sources from spectral components.
Spatial distribution of the spectral power of the magnetic noise sources, calculated from the spectra, is combined with hand picture. Also channels positions are shown.

The method of frequency-pattern analysis of the multichannel magnetic data makes it possible to reconstruct the functional structure of the various complex systems.

Applications

- Research and diagnostics of the central and periferal nervous system, including receptors.
- Research and diagnostics of the muscles.
- Localization of the magnetic nanoparticles.
- Other problems.

- Llinás R.R., Ustinin M.N. Precise Frequency-Pattern Analysis to Decompose Complex Systems into Functionally Invariant Entities*: U.S. Patent.* US Patent App. Publ. 20160012011 A1. 01/14/2016
- M.A.Polikarpov, M.N.Ustinin, S.D.Rykunov, A.Y.Yurenya, S.P.Naurzakov, A.P.Grebenkin, V.Y.Panchenko. 3D imaging of magnetic particles using the 7-channel magnetoencephalography device without pre-magnetization or displacement of the sample // *Journal of Magnetism and Magnetic Materials*. 2017. V.427. P.139-143. doi:10.1016/j.jmmm.2016.10.055.
- Llinás R.R., Ustinin M.N., Rykunov S.D., Boyko A.I., Sychev V.V., Walton K.D., Rabello G.M. and Garcia J. Reconstruction of human brain spontaneous activity based on frequency-pattern analysis of magnetoencephalography data. // *Frontiers in Neuroscience*. 2015. 9:373. doi:10.3389/fnins.2015.00373.
- Llinás R.R., Ustinin M.N. Frequency-pattern functional tomography of magnetoencephalography data allows new approach to the study of human brain organization // *Frontiers in Neural Circuits*. 2014. *V. 8. P. 43.* doi: 10.3389/fncir.2014.00043

FOUNDATIONS SUPPORTING THE STUDY

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