Superconducting QUantum Interference Device (SQUID) and applications

Massoud Akhtari PhD

Topics

- Superconductivity

  Definitions

- SQUID

  Principles

- Applications

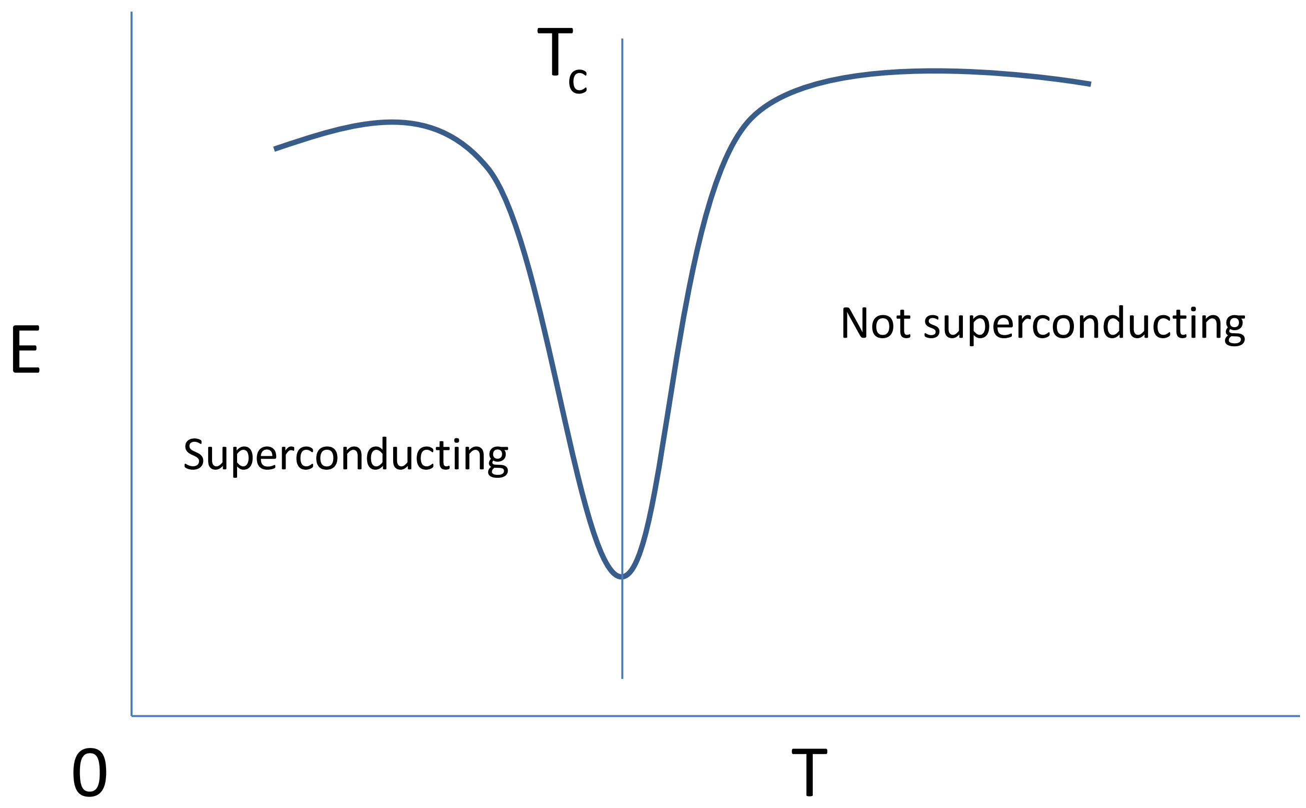
Superconductivity

- Conduction lattice has zero resistance to currents through it
  - Usually occurs at lower temperatures
    - 70K liquid nitrogen (cuprates, others)
    - ~4K liquid ^{4}helium (Niobium, lead, others)
  - Lattice vibrations decrease
  - Favorable lower energy states develop
  - Conduction mediators pair up (Copper pairs)
  - Pairs unite to form single conduction entity (cloud)

- Currents Last forever (eg. MRI)

Superconductivity

- Critical Temperature T_c



Cooper pairs

- Cooper pair is pair of individual conduction mediators that act as one unit (wave function, $\Psi = \Psi_0 e^{i\vartheta}$) due to interactions with the superconducting lattice
  - electron-phonon interaction causes pairing leading to bosons occupying lower energy state

- Can also happen with helium III and IV to form super-fluids which do not adhere to surfaces

Magnetic flux

- Magnetic flux Φ is magnetic field B (= $\nabla \times A$; A is magnetic potential; also = $\nabla \times (A + \nabla\Lambda)$, ie gauge transform) multiplied by the area (S) that it covers thus its magnitude is arbitrary and continuous

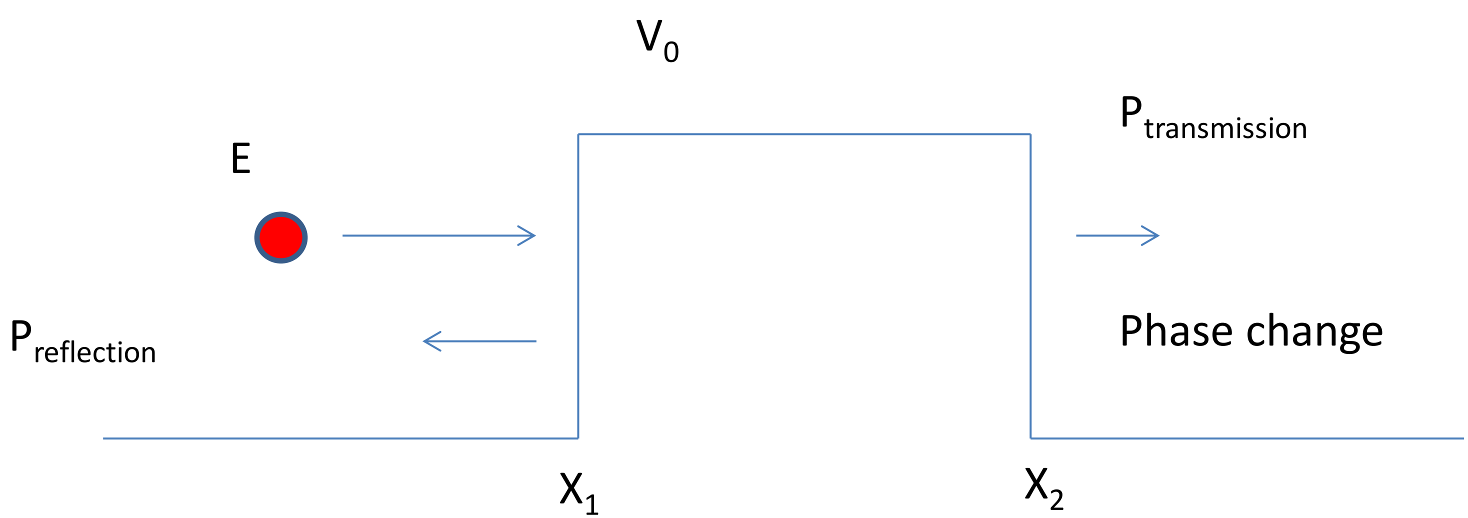
$$\Phi = \int \boldsymbol{B}.d\boldsymbol{S} \text{ or } \Phi = \oint \boldsymbol{A}.d\boldsymbol{l}$$

Quantum of Flux

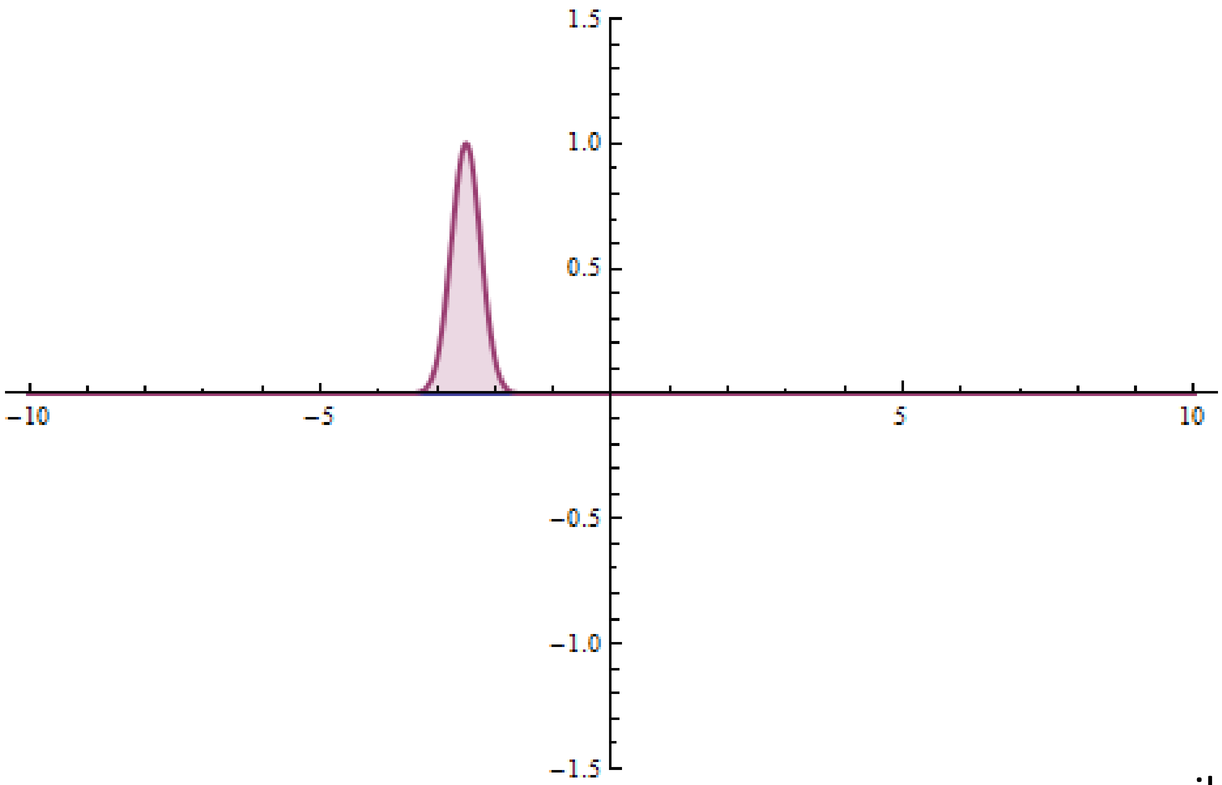
- Φ_0 is the quantum of flux that excites Cooper pairs to the next excited state (ie. same idea as excited state of hydrogen atom 21 centimeter line)
- $\Phi_0 = h/(2e) \approx 2.067833758(46)\times10^{-15}$ Wb (T.m^2)
  - h: Plank's constant
  - e: charge of electron
- Φ_0 is relatively large when expressed in T. mm^2 ~nanoT

Quantum Mechanical Tunneling

- Particles, materials, objects cross barriers when classically forbidden
- Tunneling changes amplitude and phase of Ψ
- Tunneling coefficient $T(E) = e^{-2\sqrt{\frac{2m}{\hbar}(V_0 - E)}(x_2 - x_1)}$



Quantum Mechanical Tunneling



wiki

Measuring Magnetic Flux

- Can use a magnetometer

wiki

Measuring Small Magnetic Flux

- Problem: Can measure down to a small enough flux until the induced current becomes similar or smaller that the thermal motion (noise) of the lattice and conduction electrons

- Solution: Decrease thermal noise by decreasing conductor temperature to create superconductor

- Problem: Can measure down to Φ_0 with superconductor; how can measure lower than Φ_0 : needed for measuring flux due to biological activity

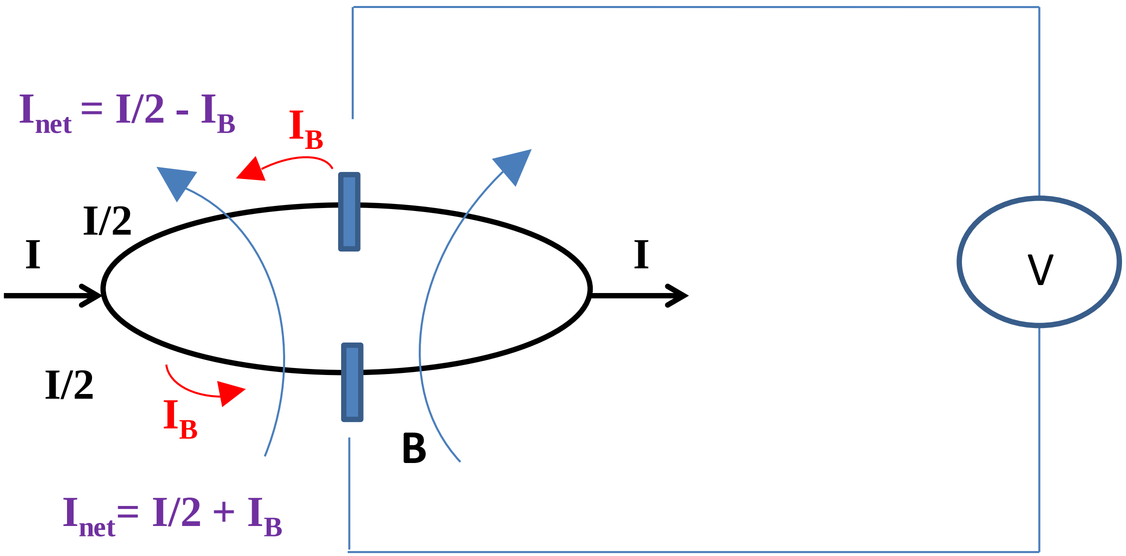
Measuring Small Magnetic Flux

- Add two thin resistors (Josephson junctions) into the superconducting loop to introduce tunneling

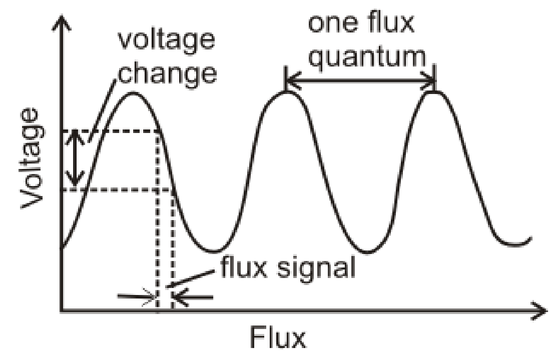
Measuring Small Magnetic Flux

- Josephson junction introduces tunneling effect in the loop to allows the phase of the Cooper pair (cloud) to change with respect to itself while going around the loop leading to change in current amplitude due to interference
  - think of it as a snake eating its own tail

Measuring Small Magnetic Flux



Measuring Small Magnetic Flux



- Without external field

  $I = I_c(t) \sin v(t)$,

  where v is the phase change due to the barrier (JJ)

  Note current I varies in the range of critical current $-I_c$ to $+I_c$ (state changes by Φ_0 at each I_c)

- With external field

$$\Delta\chi_a = \nu_a + \left(\frac{e}{\hbar}\right) \oint \boldsymbol{A}.\, d\boldsymbol{l}$$

  where $\Delta\chi_a$ is the resulting phase change in top loop; similar term also for bottom loop

Measuring Small Magnetic Flux

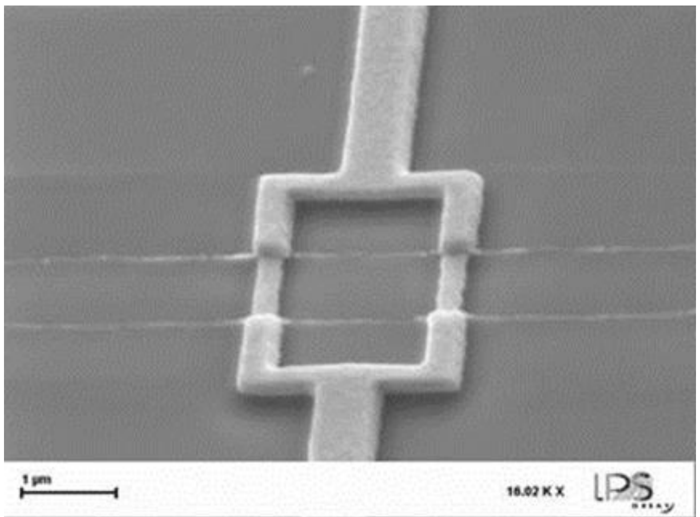
- The new total current due to external flux:

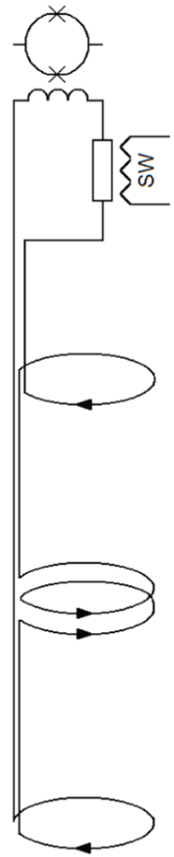
$$I = I_c sin\frac{\nu_a - \nu_b}{2}\cos[\left(\frac{e}{\hbar}\right)\Phi]$$

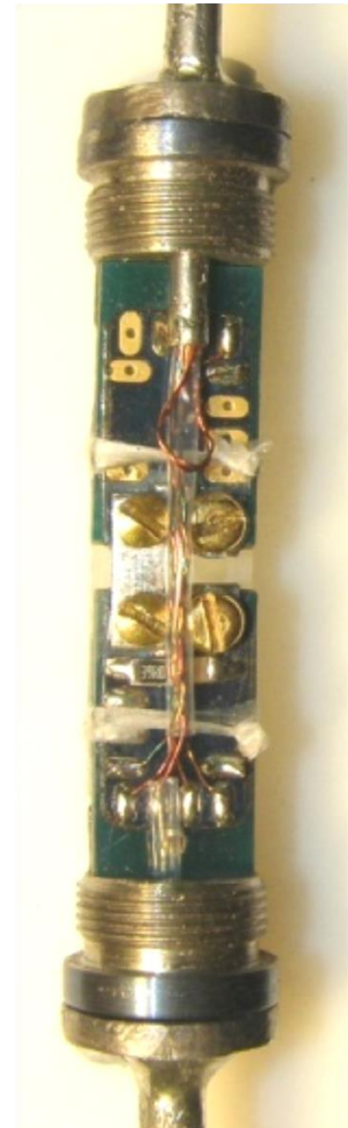
- AC SQUID

$$V(t) = \frac{\hbar}{2e}\frac{\partial \nu}{\partial t}$$

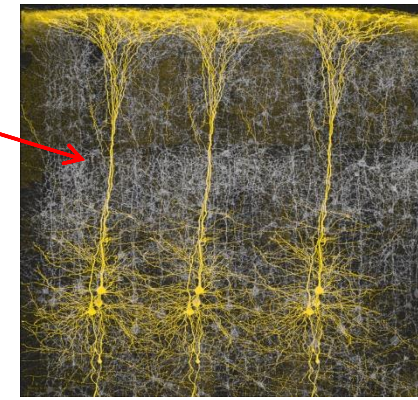
SQUID Gradiometer







Magnetic Fields of the Brain



Single neuron:

Using a current dipole model: $\mathbf{B} = \frac{\mu_0}{4\pi} \cdot \frac{\mathbf{Q} \times \mathbf{r}}{r^3}$

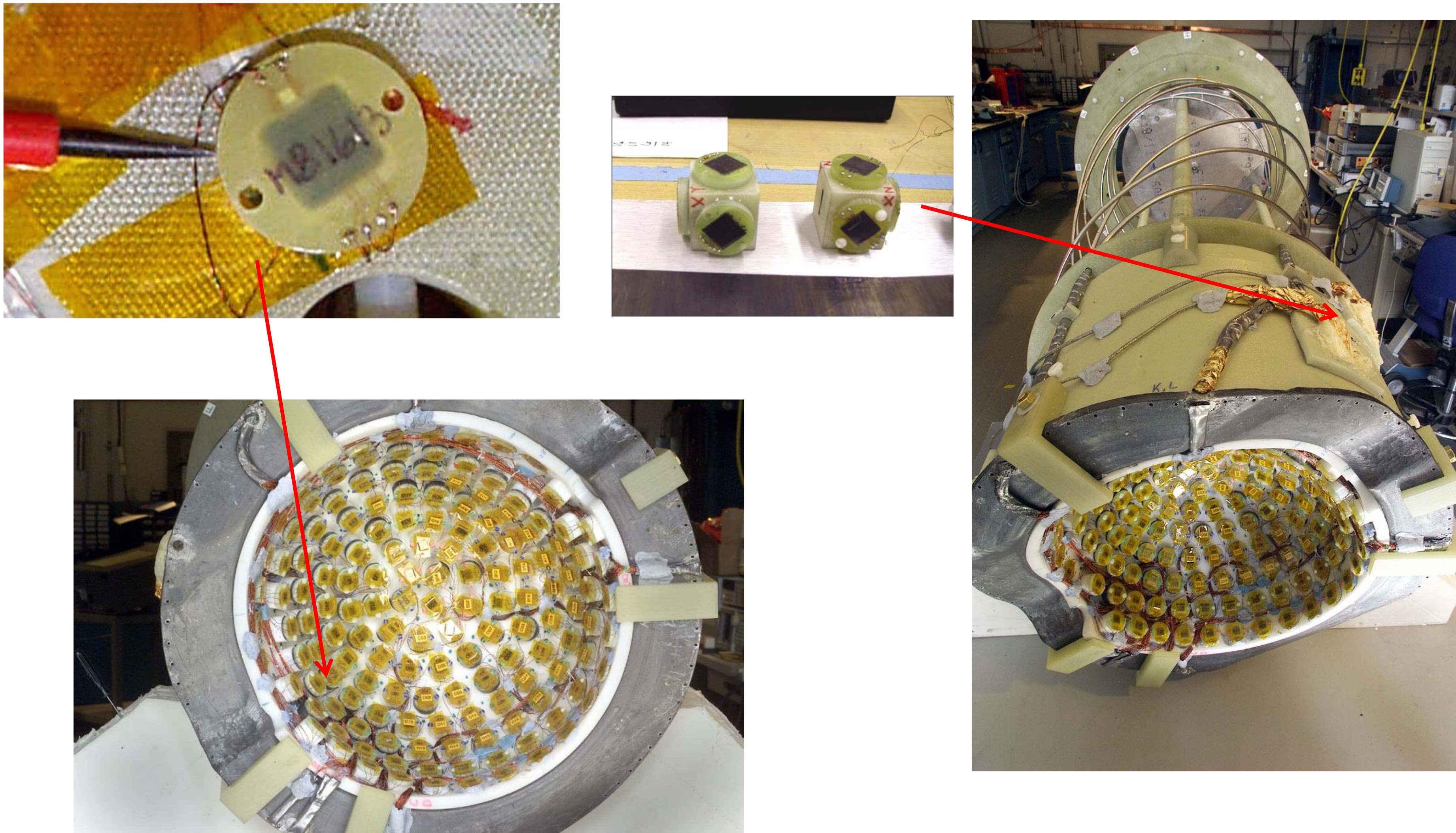
Post-synaptic potential: Q~20 fA·m => B~20 pT @ 10 μm
Action potential: Q~100 fA·m => B~100 pT @10 μm

Cortex patch:

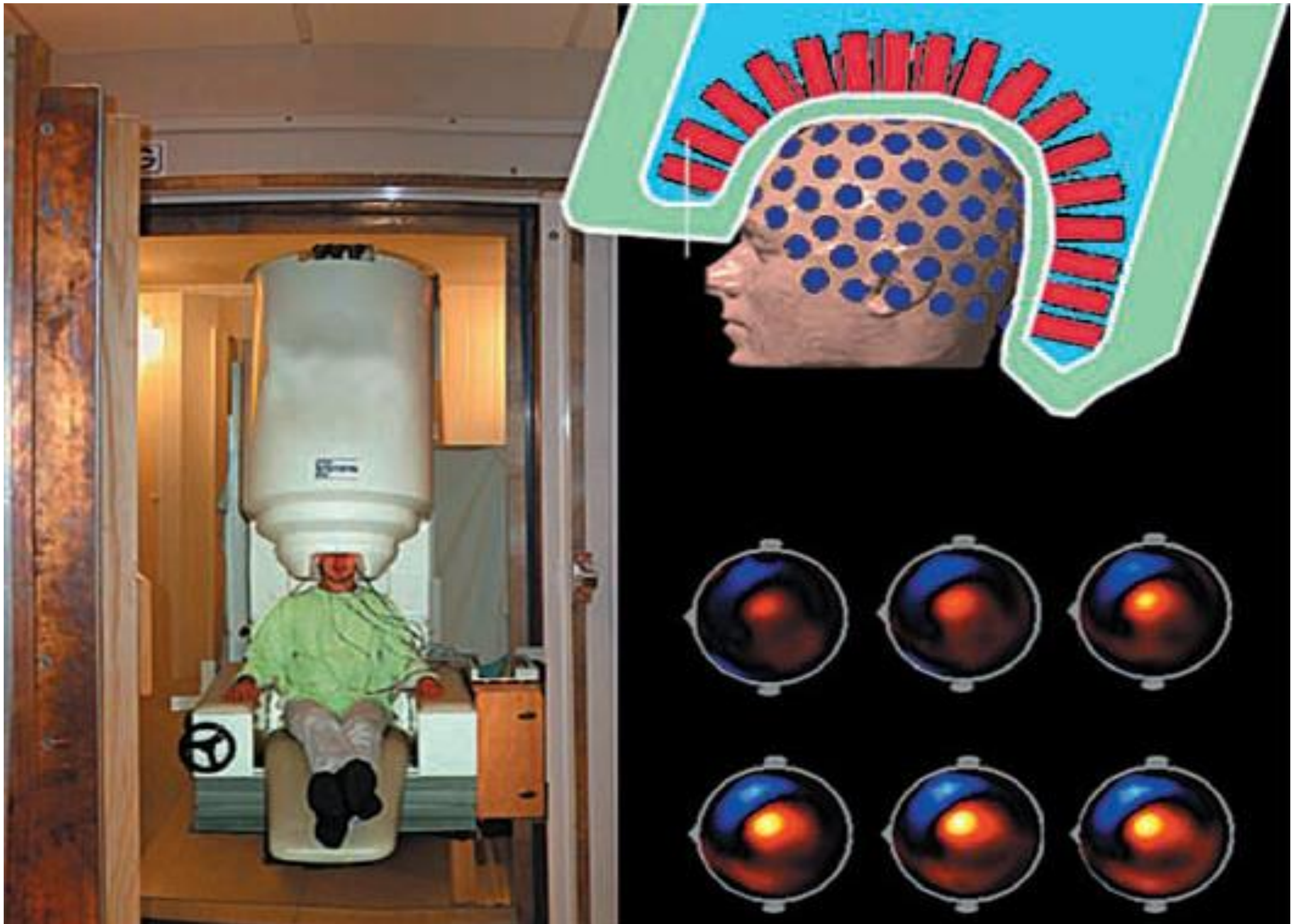
Cortex current ~100..250 nA/mm^2; and
Active cortex area S ~ 50 mm^2 (R = 4 mm x h = 1 mm)
The field:
Inside the cortex B~30 pT, outside the cortex (@ 30 mm) B~1 pT

Ref: Hämäläinen, M. et al, Rev Mod Phys, 65:413-497 (1993).

Magnetoencephalography (MEG)

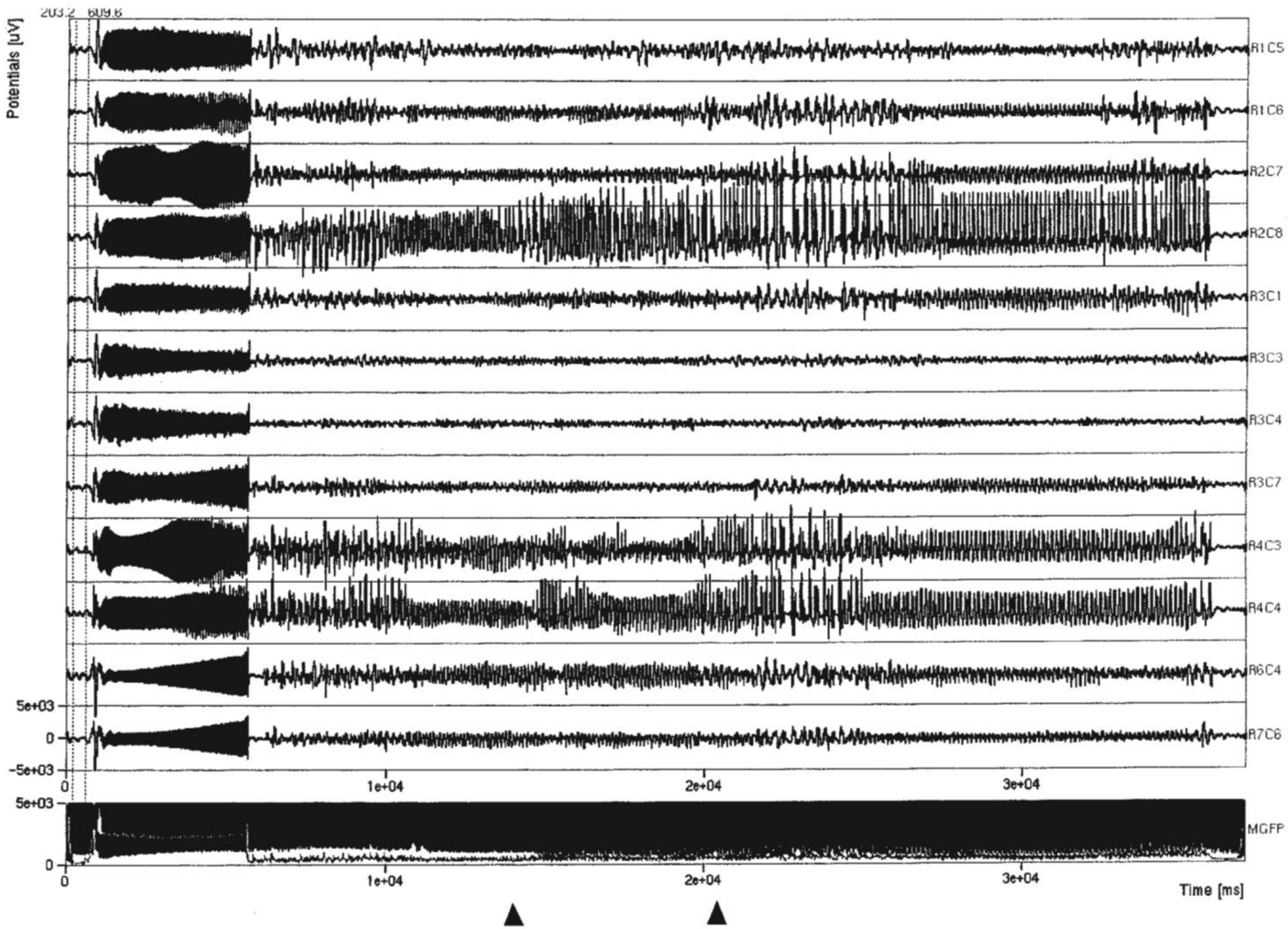


MEG



Bailett et al 2001

MEG



Sutherling, Akhtari, et al 2001

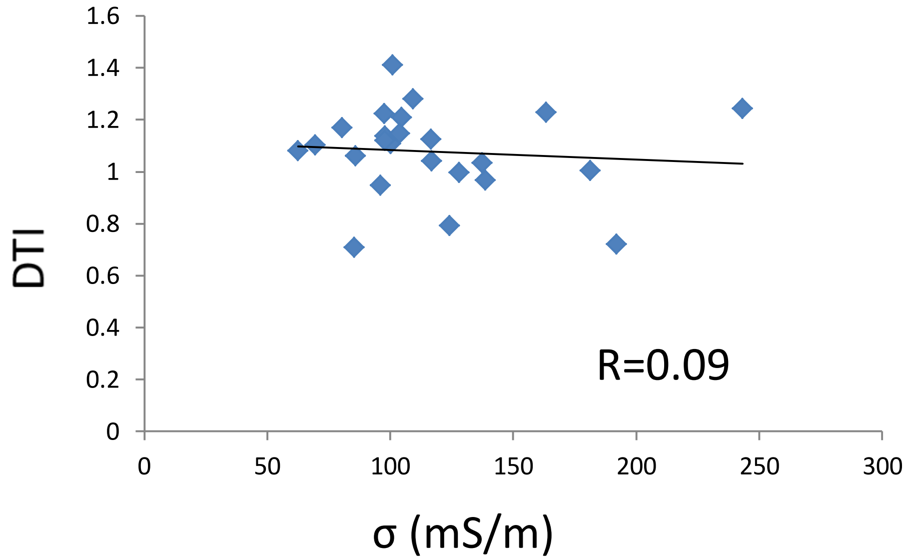
MEG

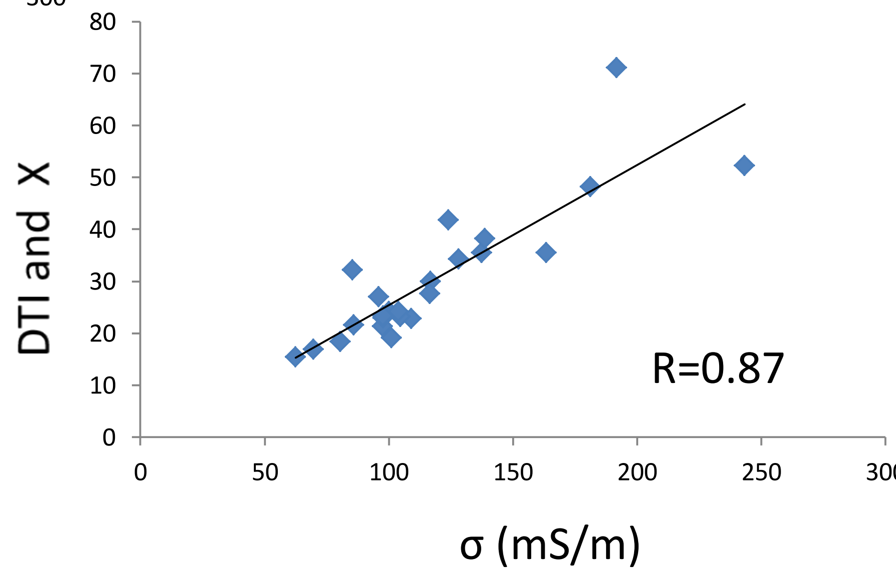
- Mathematical model of source localization

$$(\boldsymbol{r}) = B_0(\boldsymbol{r}) + \frac{\mu_0}{4\pi}\sum_{ij}(\sigma_i - \sigma_j)\int_{S_{ij}} V(\boldsymbol{r}')\frac{\boldsymbol{r}-\boldsymbol{r}'}{||\boldsymbol{r}-\boldsymbol{r}'||^3} \times d\boldsymbol{S}'_{ij}$$

$$(\sigma_i - \sigma_j)V(\boldsymbol{r}) = 2\sigma_0 V_0(\boldsymbol{r}) - \frac{1}{2\pi}\sum_{ij}(\sigma_i - \sigma_j)\int_{S_{ij}} V(\boldsymbol{r}')\frac{\boldsymbol{r}-\boldsymbol{r}'}{||\boldsymbol{r}-\boldsymbol{r}'||^3} \times d\boldsymbol{S}'_{ij}$$

Conductivity





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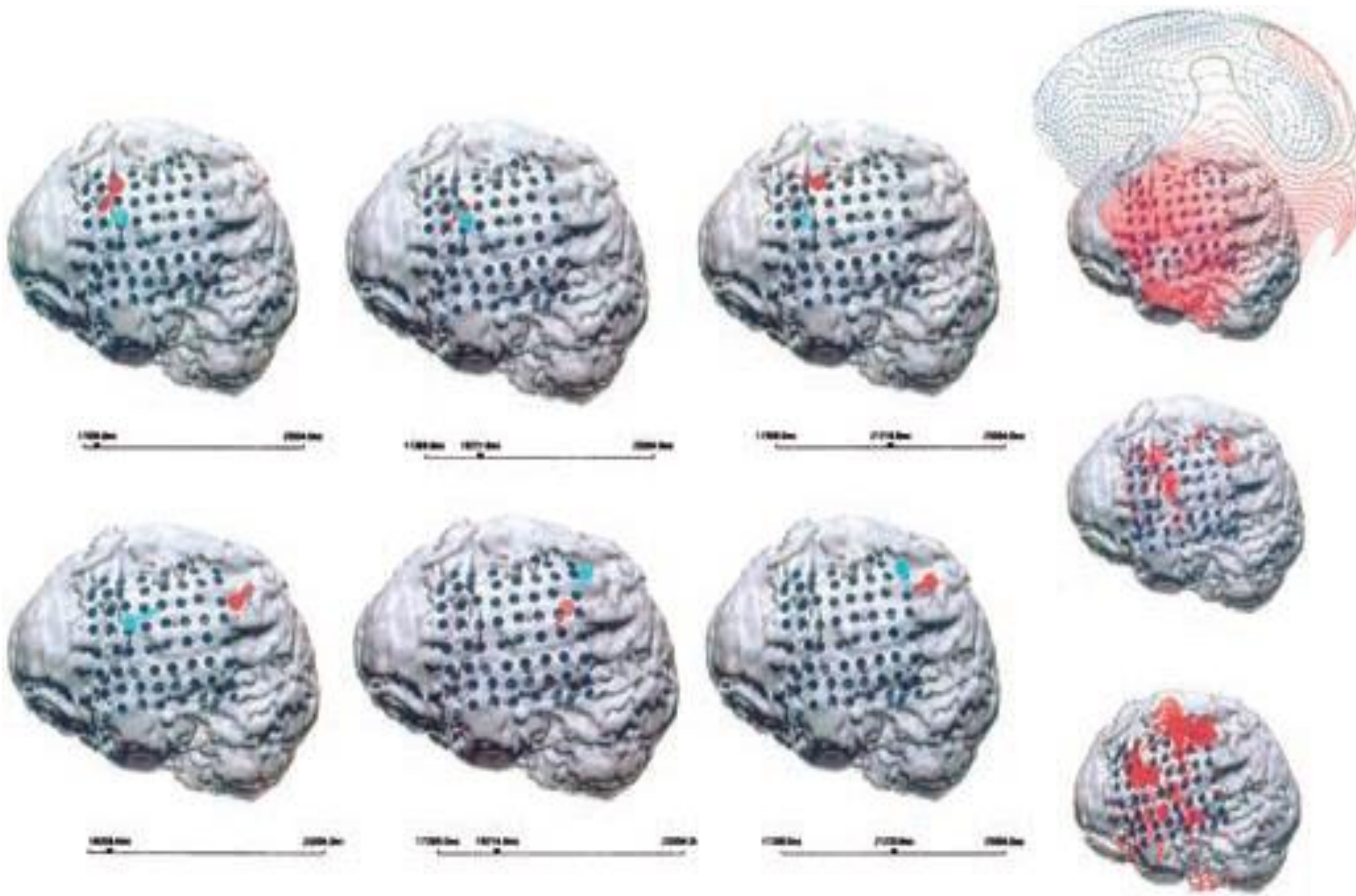
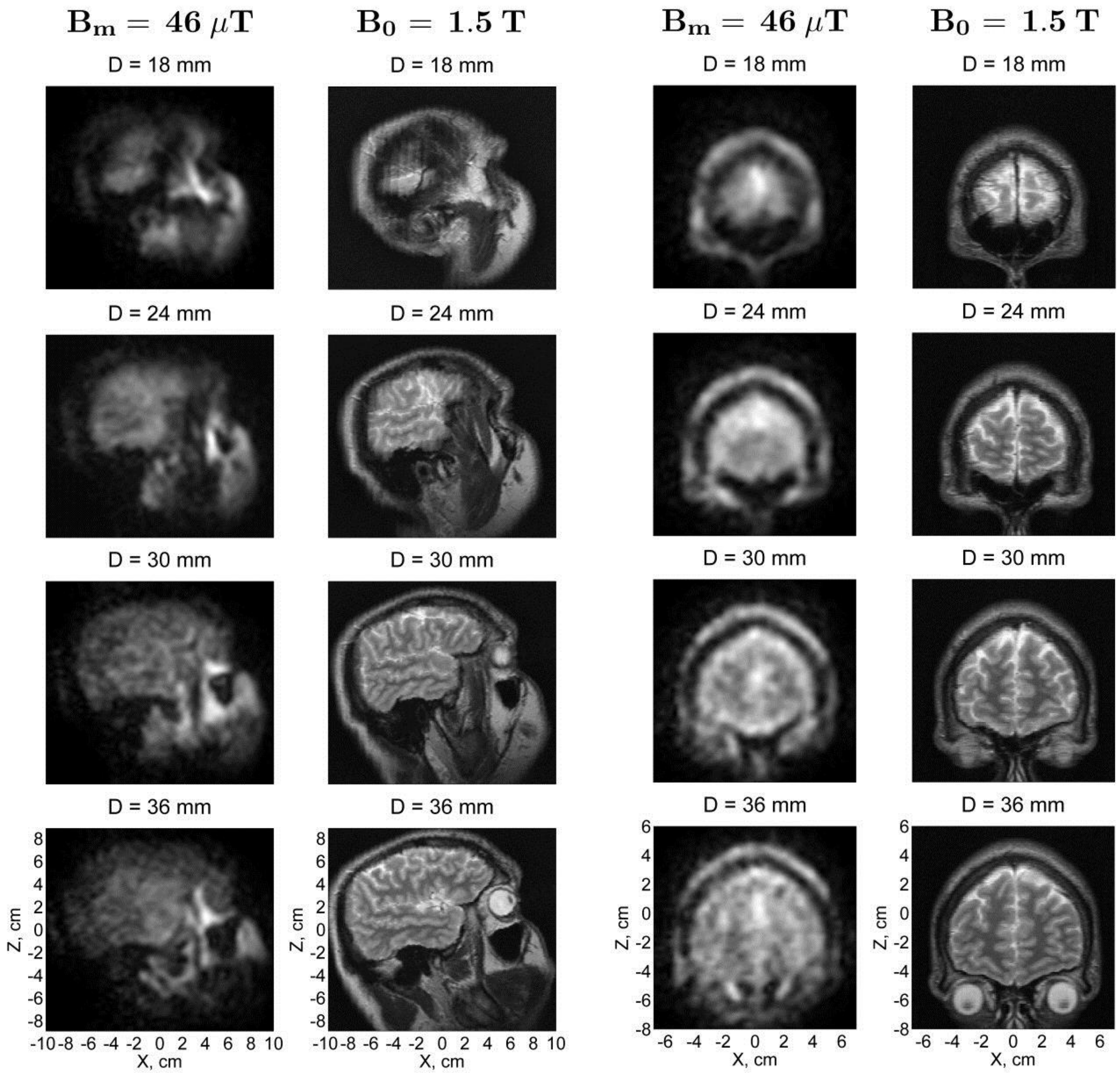


Sutherling, Akhtari, et al 2001

SQUID MRI



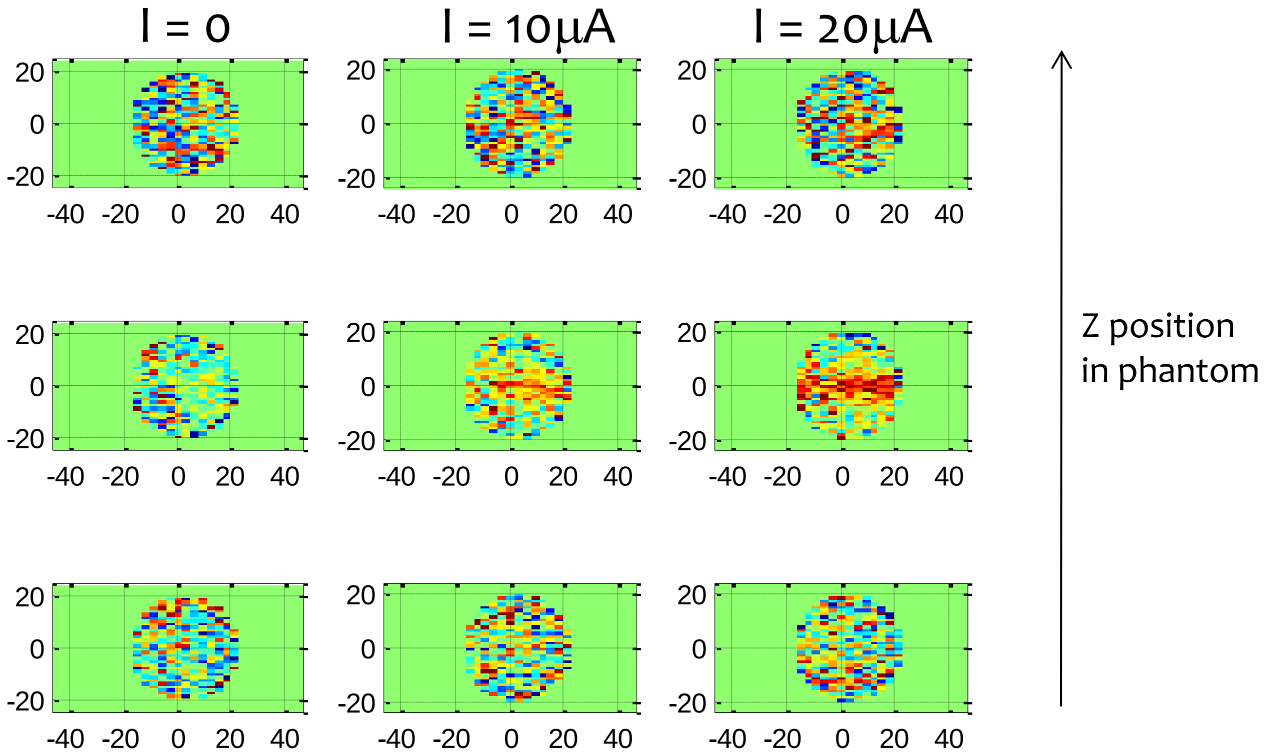
Matlachov et al
2008

Functional (SQUID) MRI

Current in wire phantoms

3D Imaging experiments using current phantom

- Able to detect a signal from wire at 10μA (DC)



Maskaly et al 2009

Security Screening

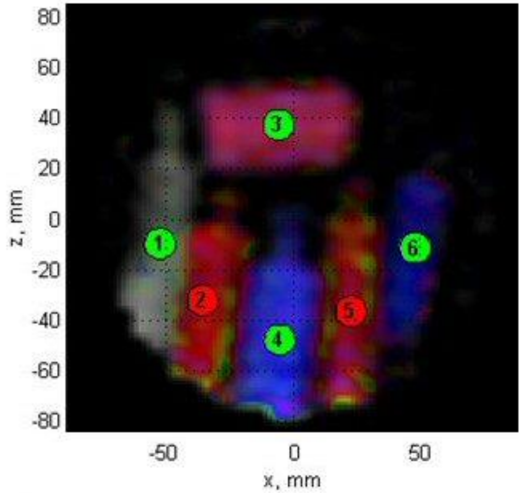
SQUID MRI numbers

Substance	T1 (mSec)	T2 (mSec)
Wine #1 chardonnay	**880 ± 40**	**590 ± 10**
Wine #2 shiraz	**1100 ± 40**	**780 ± 10**
Wine #3 chardonnay	**1050 ± 40**	**700 ± 40**
Whiskey	**1410 ± 40**	**1230 ± 10**
Brandy	**1600 ± 40**	**1340 ± 10**

Security Screening

ULF MRI can provide information about packed bags and bottles content as well as the content quality

Food quality and Security screening:
Differences in MR relaxation parameters are used to identify different liquids

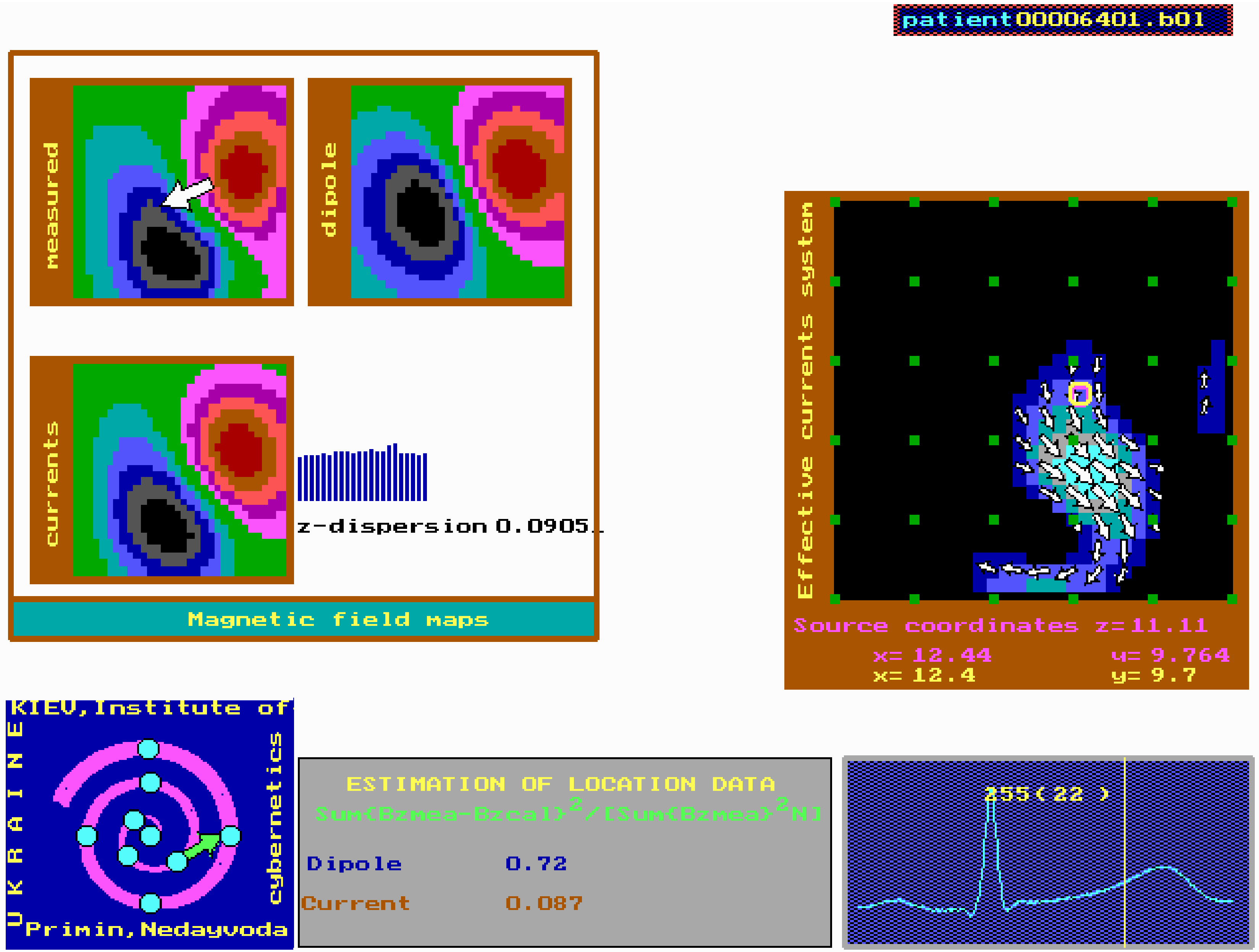


Matlachov et al 2008

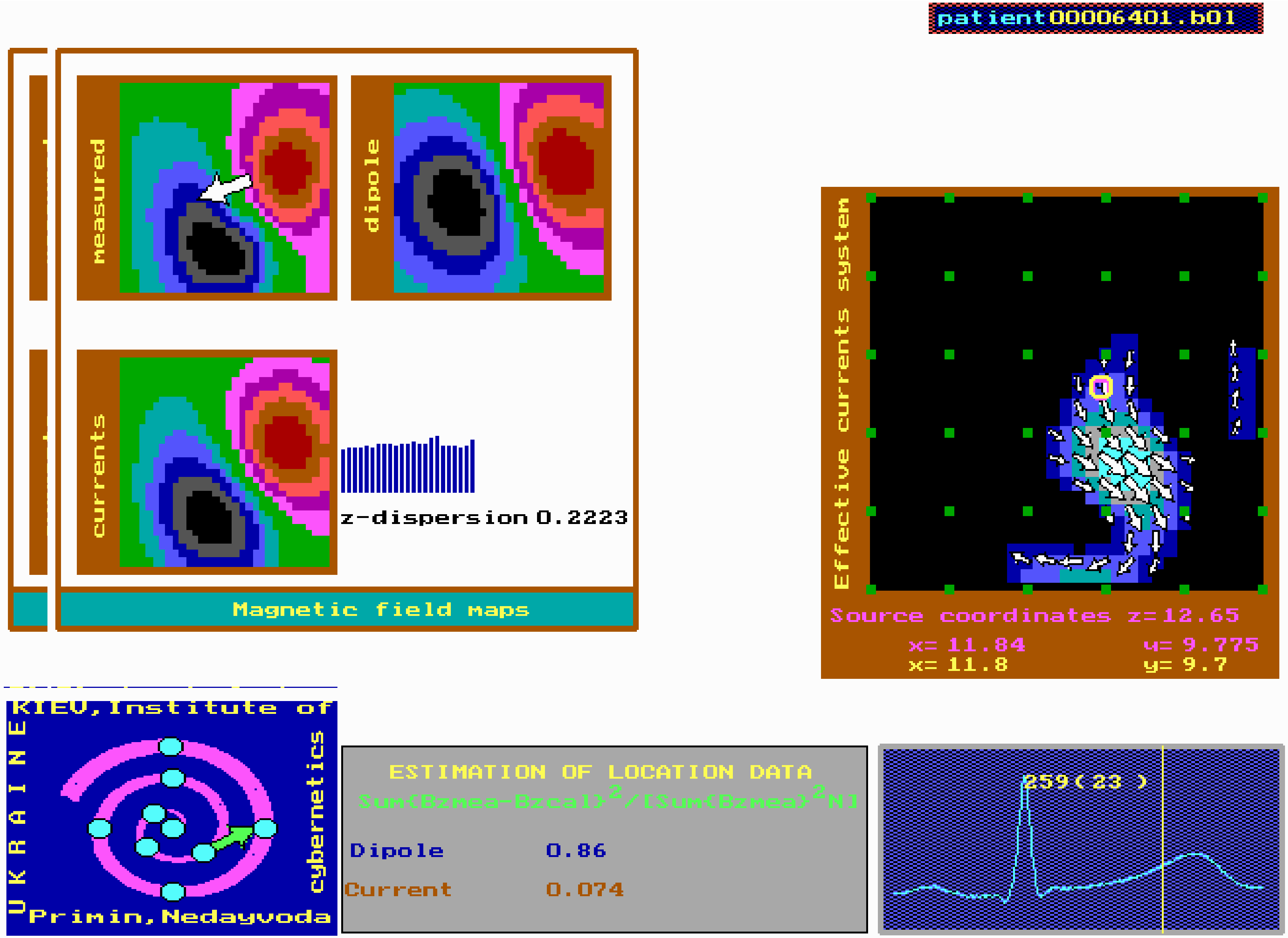
A quart-size airport bag with bottles of liquids

2D MRI image acquired at 46 μT with automatic liquid classification: green label – safe, red -- dangerous

Healthy person



Healthy person



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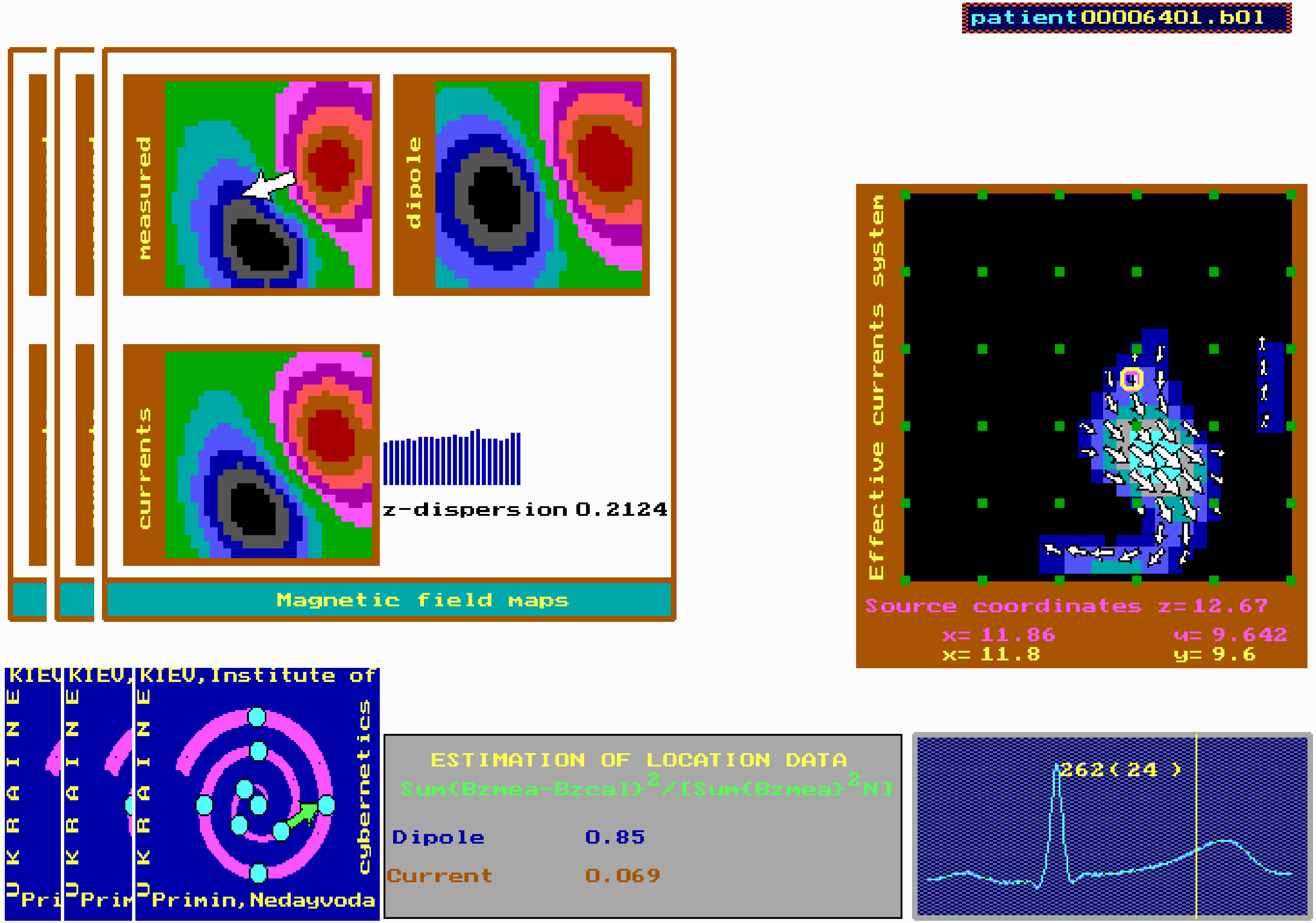

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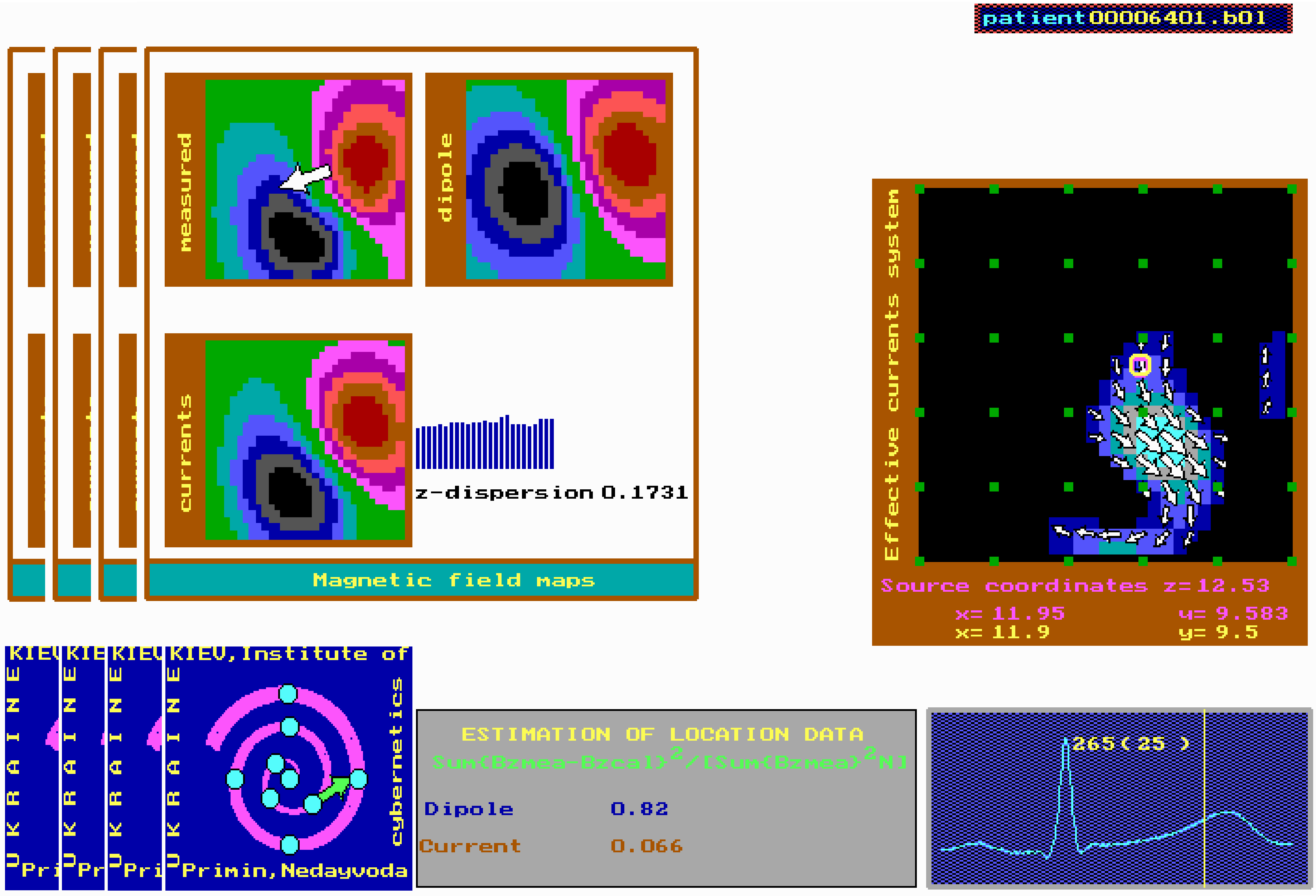
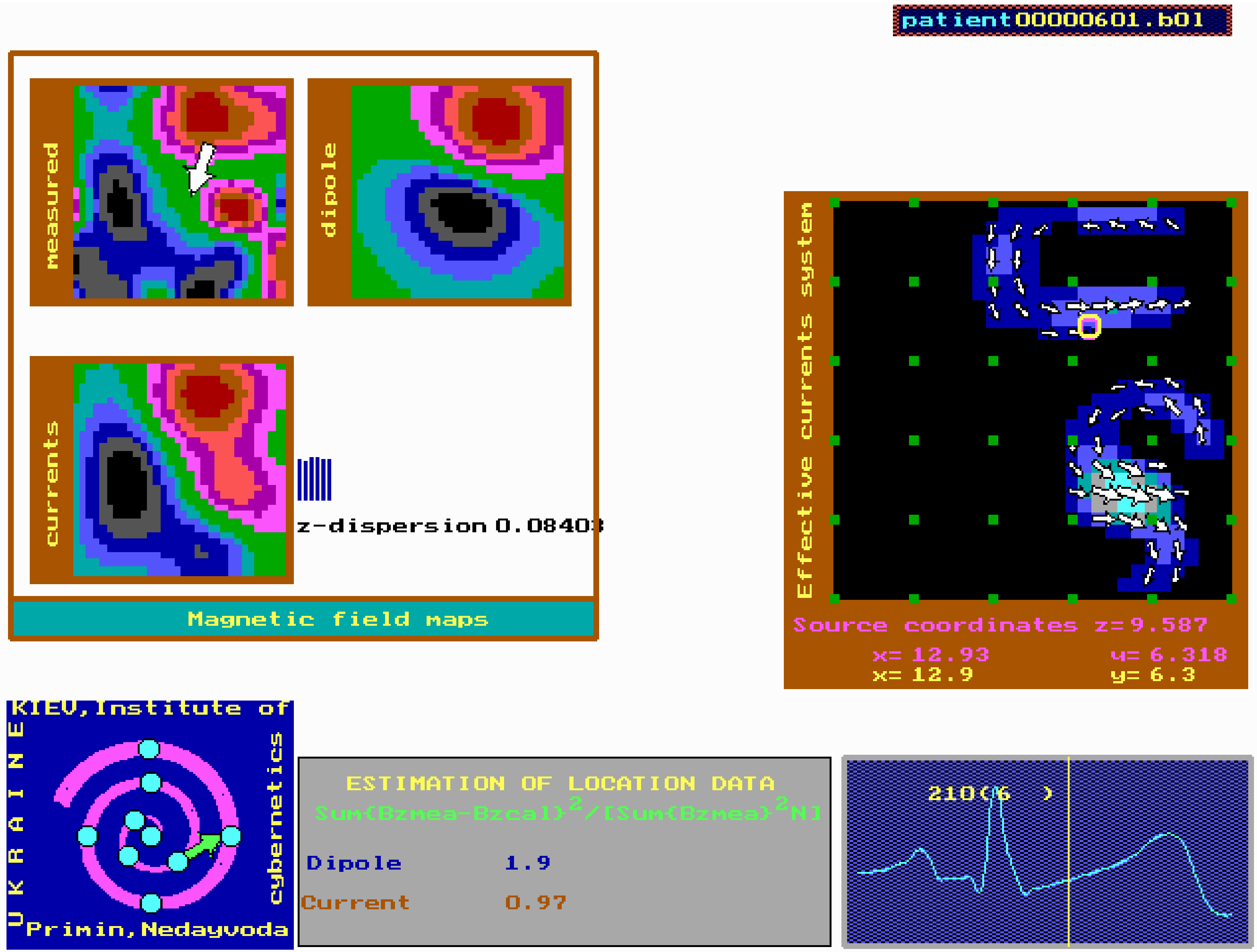


Patient with initial ischemia



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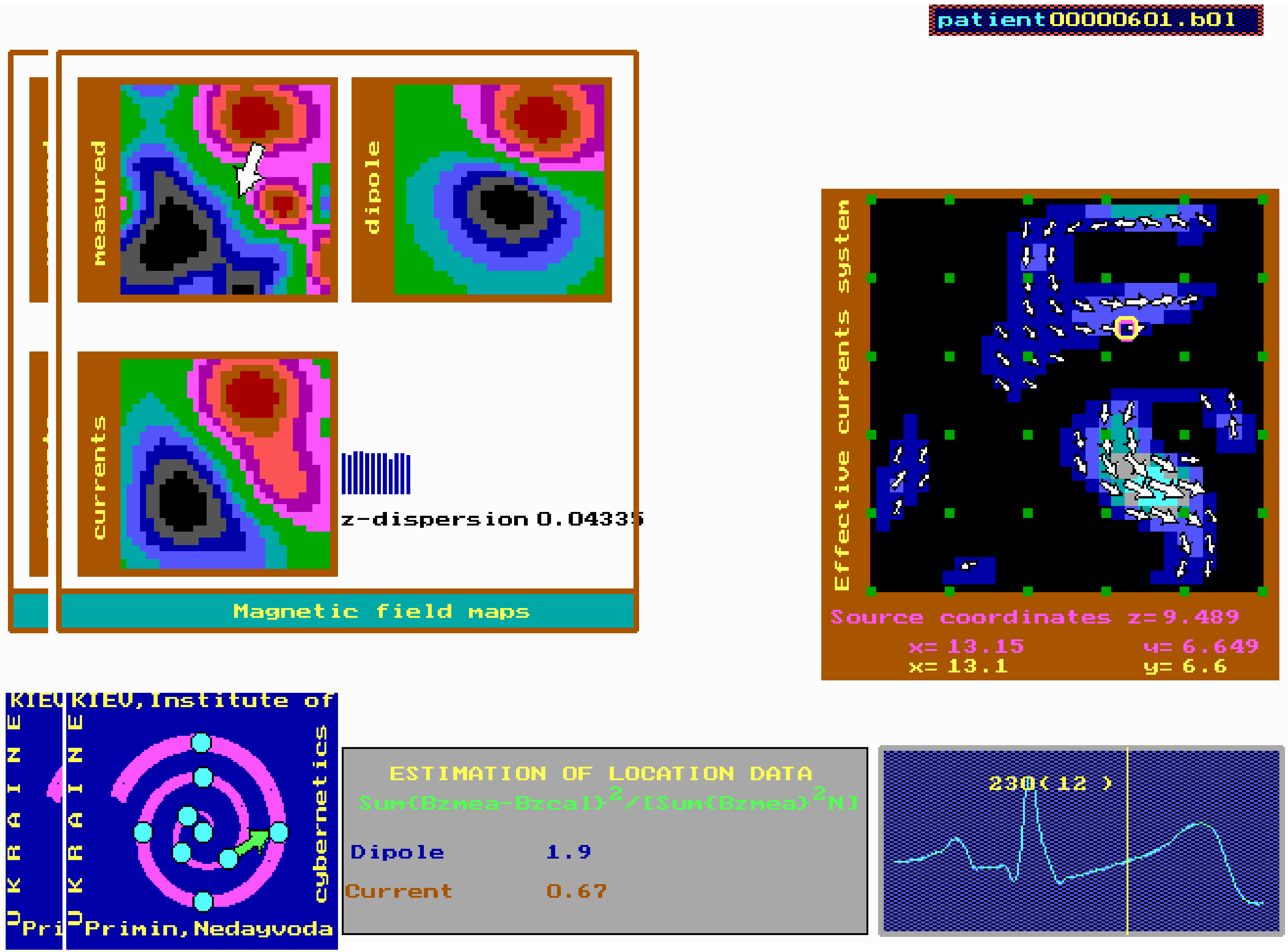
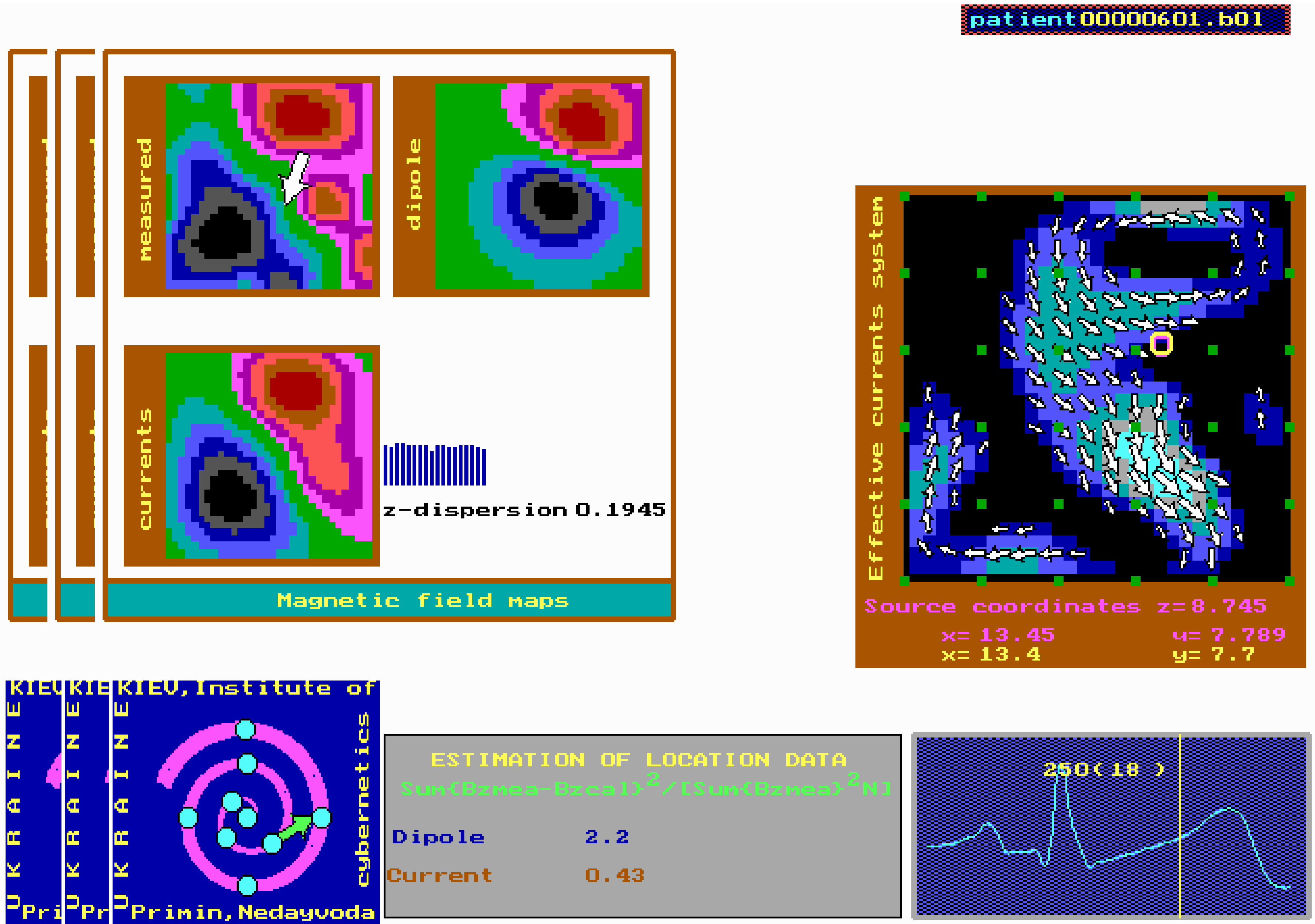
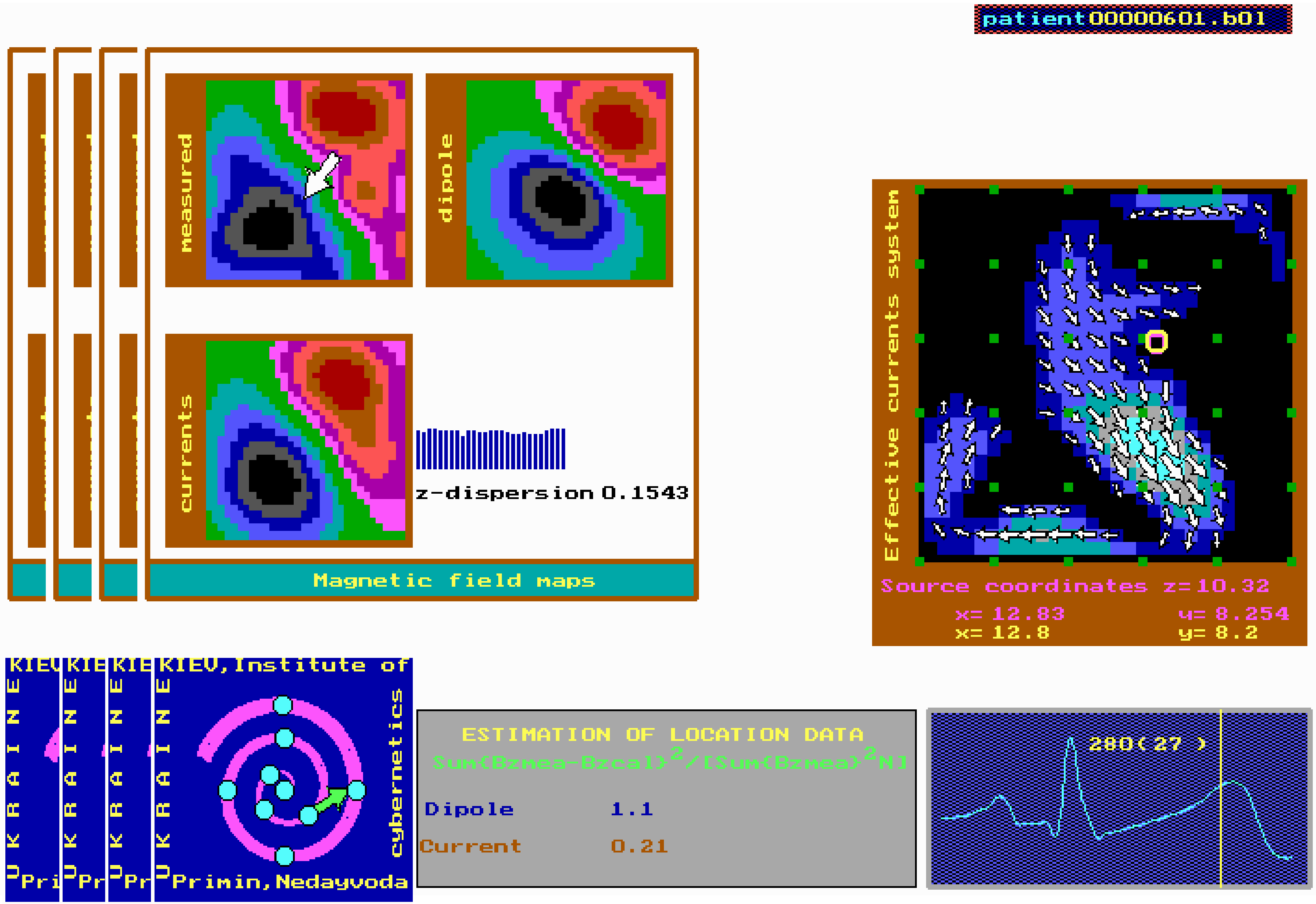


Patient with initial ischemia



Patient with initial ischemia



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